Electrical Transmission of Energy

THORNTON

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Edited by R. E. NEALE, B.Sc., Hons. (Lond.)
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FIRST PRINCIPLES OF THE ELECTRICAL TRANSMISSION OF ENERGY

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FIRST PRINCIPLES OF THE

ELECTRICAL TRANSMISSION OF ENERGY

A SURVEY OF THE PHYSICAL BASIS OF ELECTRICAL TRANSMISSION, ITS METHODS AND PHENOMENA FROM THE STANDPOINT OF THE ELECTRON

FOR STUDENTS AND PRACTICAL ENGINEERS

BY

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PREFACE

THESE notes are the substance of a course of six informal lectures to the members and students of the Institution of Electrical Engineers in Newcastle, partly repeated at Middlesbrough. They were taken almost verbatim by Mr. N. Thornton and Mr. L. C. Grant, of Messrs. Merz and McLellan's staff, to whom the author is much indebted, and have, therefore, more of the character of the spoken than the written word.

The lectures were intended to give to an audience of practical engineers and students a rapid survey of the physical basis of electrical transmission from the standpoint of the electron, not yet usual in engineering literature. The notes on transient phenomena were added by request.

W. M. THORNTON.

NEWCASTLE-UPON-TYNE,
January, 1921.

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GREEK LETTERS USED

α—alpha—Number of negative ions produced by one ion in travelling a centimetre length of field.

β—beta—Number of positive ions produced.

ϵ—epsilon—Basis of natural logarithms (= 2·718...)

λ—lambda—Wave length.

μ—mu—Permeability of iron.

ρ—rho—Resistivity.

σ—sigma—Electrical conductivity.

FIRST PRINCIPLES OF THE ELECTRICAL TRANSMISSION OF ENERGY

All electrical theory and practice is based upon the ether, the properties of which must therefore be considered first.

1. The Ether has Tensile Strength.

The evidence of this is mainly from astronomy. When a stone is whirled round at the end of a string, it is kept in its path by the string's tension. In the case of the moon revolving around the earth, the ether in the space between them represents the string, and is attached rigidly to the earth, the centre of rotation, and to the moon.

The force on the mass of a ton at the earth's surface is one ton weight, and it is known that the force falls off inversely as the square of the distance of the mass from the earth's centre. The mass of the moon is 75×10^{18} tons, and the distance between the centres of

earth and moon is sixty times the earth's radius. The pull at this distance on a ton would be 1/3,600 of a ton weight. The total pull on the moon is then $75 \times 10^{18}/3,600$, or 2×10^{16} tons weight. If it is taken that the whole of this is carried by a rod of ether connecting the two, its tension at the surface of the earth is thousands of times greater than the strongest steel could carry. The ether that sustains the pull is, therefore, woven into the whole fabric of the earth to the centre, and at the surface is carrying a tension far greater than the matter of the earth's crust itself could support.

The ether cannot be compressed by matter, though it will be shown that in the making of the positive electron or atomic nucleus there is evidence of compressional strain.

2. The Ether has Torsional Strength.

All electrical phenomena are associated in some way with, and may be represented by, a twist in the ether, such, for example, as the curl of a magnetic field around a current, or of electrostatic tubes of force. The atoms on which gravitational force acts are themselves a combination of circulations, and it is not

unlikely that, in gravitation. the ether takes hold of matter by means of interwoven torsional strains.

3. The Ether is Elastic.

So far as is known, the ether is a perfectly elastic medium. It is again from astronomy, and the marvellous precision with which the phenomena of planetary rotations about the sun recur, that we have the strongest evidence of the absence of friction between ether and matter. So far as gravitational strain is an index, the ether is elastic, and does not take a permanent set on a large scale, though it must do so in the extremely minute bodies that are the units of electric charge.

Further evidence of the elasticity of the ether is furnished by the fact that it is able to transmit waves. These are elastic electromagnetic vibrations in which the electric movement is perpendicular to the line of advance of the wave. Wireless waves, radiant heat, light and X-rays, are all the same in type and proceed with the same velocity, viz., 3×10^{10} cm. per sec.

In *travelling elastic vibrations*, the distance from the maximum of one wave to that of

the next is the wave length, and is represented by λ, Fig. 1, when the horizontal axis gives distance of travel; by T, the periodic time, when the horizontal axis is one of time;

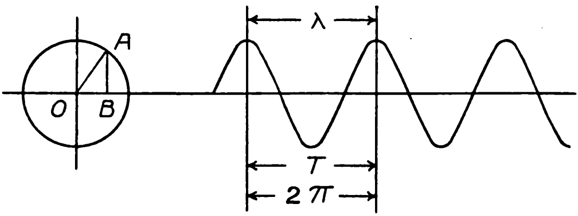

FIG. 1.—TRAVELLING ELASTIC VIBRATIONS. SIMPLE HARMONIC MOTION.

and by 2π, the angle of one revolution of OA (the projection, AB, of which is the ordinate of the curve), when the curve is drawn to a base of angular displacement AOB.

Take the illustration of a swinging pendulum, or of a vibrating spring carrying a weight. The motion can be traced out in the form of a curve on paper moving uniformly at right angles to the direction of motion. Or consider the case of elastic motion of a body of mass m from a central position of rest, Fig. 2. Let the body be moved from that position through a distance x. The force restoring it

to the centre is proportional to the displacement, and since it has inertia it requires a force to accelerate it equal to the product of the mass and the acceleration at x. Let E be the force to displace it to unit distance.

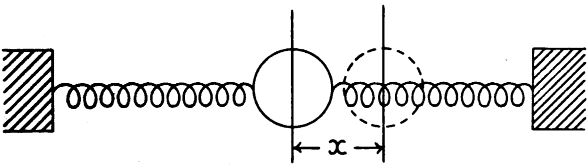

FIG. 2.—ELASTIC MOTION FROM CENTRAL POSITION OF REST.

This force is termed the *elastic coefficient* and the restoring force F, when the body is at $x = E \times x$. When swinging freely along a horizontal line, the only forces acting are the tension of the spring and that due to inertia, so that $Ex = ma$. This is the first condition for an elastic oscillation.

The natural curve of transition from a positive to a negative maximum without shock, the easiest possible mode of continuous oscillation, is a sine wave. Let the position of the body in Fig. 2 vary so that—

$$x = A \sin pt\,;$$

where A is the maximum displacement on either

side of the centre, t the time from the position of rest to reach x, f the frequency of oscillation, and $p = 2\pi f$ the angular velocity of OA in Fig. 1.

The velocity v of displacement at x is—

$$v = \frac{dx}{dt} = p\, A \cos pt,$$

and the acceleration is—

$$a = \frac{dv}{dt} = -p^2\, A \sin pt = -p^2 x.$$

So that $-Ex = -m\, p^2 x$ (*minus* Ex because the force of the spring draws the body back to rest).

$$\text{Thus} \quad p = \sqrt{\frac{E}{m}}, \text{ and } f = \frac{1}{2\pi}\sqrt{\frac{E}{m}}.$$

E is the elastic coefficient of the system, mass is the inertia coefficient; and for all elastic systems with inertia the frequency of free oscillation is given by—

$$f = \frac{1}{2\pi}\sqrt{\frac{\text{the elastic coefficient}}{\text{the inertia coefficient}}}.$$

Free waves in the ether are examples of such a system, as well as oscillations on wires or transmission lines.

4. Electrostatic Capacity.

In free space the elastic coefficient of the medium is the reciprocal of the electrostatic capacity of unit cube. Consider first any system of charges, Q, each held apart by a difference of potential V. The capacity K of the system is defined as the ratio Q/V, so that the displacement $Q = K \times$ displacing force V. Now we took as the definition of the elastic coefficient, E, the ratio force/displacement (§3), hence $1/K$, the reciprocal of the electrostatic capacity, is analogous to E, the elastic coefficient.

Consider next a cube in space of side d, the area of the faces A, and let the dielectric constant or specific inductive capacity of the space be k. The capacity of the cube when opposite faces are charged is—

$$K = \frac{kA}{4\pi d},$$

and of unit cube is $k/4\pi$. Thus, in wireless working, if we are sending a wave through space in which the charges due to electric displacement may at any moment be supposed to be concentrated on two opposite faces

of the cube, its capacity will be $k/4\pi$, and its elastic coefficient will be $4\pi/k$ per unit length of its path.

5. Electrical Inertia.

When a magnetic field is being cut by a moving body, whether a conductor or not, an electromotive force is induced in the body proportional to the rate of cutting, the value of this e.m.f. being—

$$e = -\frac{dN}{dt},$$

the number of lines or tubes of magnetic force cut per second.

The sign is negative, since when the lines linked with the circuit are increasing in number, the electromotive force induced by them opposes the applied e.m.f. of the circuit.

Self induction is the cutting of the wire carrying a current by the magnetic field the current itself sets up, whenever the current and, therefore, the field, changes. The character of this field will be considered later. The *coefficient of self inductance* L is defined as the number of lines of force linked with a

circuit when unit absolute current flows in it or—

$$L = \frac{N}{i};$$

where i is the current in c.g.s. units. L is a constant, and—

$$e = -\frac{d}{dt}(Li) = -L\frac{di}{dt},$$

analogous to force = mass × acceleration. L is analogous to mass; current i, the rate of electrical displacement, is analogous to velocity; and the rate of change of current $\frac{di}{dt}$ is analogous to acceleration.

Let H be the intensity of magnetic force in a coil of length l, having T turns carrying a current i. It is shown in text-books that $H = 4\pi iT/l$ dynes on unit magnetic pole. The flux density B in the core of area A and permeability $\mu = \mu H$. The total flux $N = BA = 4\pi iTA\mu/l$.

The flux linked with the coil, each turn surrounding the core flux N once, $= NT = 4\pi T^2/\frac{l}{A\mu}$ for unit current. The quotient

$l/A\mu$ is the magnetic reluctance of the core and may be written R. Then—

$$L = \frac{4\pi T^2}{R},$$

a formula of universal application. The difficulty is usually to find R.

Let us take this expression and consider it applied to unit cube in space, with a current flowing across from one face of the cube to another at right angles to the direction of advance. Here T, A and l are each unity, and $L = 4\pi\mu$ the *inertia coefficient of free space* in the units we are using. The *frequency of free oscillations*, such as light or wireless waves, is that of the transmitter, namely—

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{KL}},$$

where K and L are the capacity and inductance of the oscillator.

It is a well-known theorem in physics that the *velocity of transmission* in an elastic medium is—

$$v = \sqrt{\frac{\text{the elastic coefficient}}{\text{the inertia coefficient}}}.$$

Hence the velocity of transmission along the wires of an aerial is $v = \frac{1}{\sqrt{KL}}$, and the velocity of transmission in free space is—

$$v = \sqrt{\frac{4\pi/k}{4\pi\mu}} = \frac{1}{\sqrt{k\mu}},$$

so that, in free space, $v^2k\mu = 1$. This could be got from Fig. 1 by putting $\lambda = 2\pi$ and remembering that $v = f\lambda$.

Within the range of the formula $v^2k\mu = 1$ we have—

X-rays of wave length $\lambda = 0{\cdot}2$ to $1{\cdot}2 \times 10^{-7}$ cm.,

Light rays of mean wave length 5×10^{-5} cm.,

Heat rays of wave length 5×10^{-3} cm., and

Wireless waves of wave length from a few centimetres to many kilometres.

Since in free space there is no friction, the energy of the whole must be equally divided between the two forms, kinetic and potential. The energy at the end of a swing is potential energy of charge, whilst in the centre of the swing it is all kinetic. The energy of a charged condenser is $\frac{1}{2}KV^2$, and of an electromagnetic field $\frac{1}{2}Li^2$, so that—

$$W = \tfrac{1}{2}KV^2 + \tfrac{1}{2}Li^2$$

is the *total energy of the wave.* At the end of the swing $V = V_0$ the maximum voltage and $i = o$. If then we can find the energy per cubic centimetre of space, V_0 can be found; and in the same way i_0 the maximum current when $V = o$, is determined.

The *amount of energy received* per second on a square centimetre in full sunlight is vw, where v is the velocity of light in cm. per sec., and w is the energy in a cubic centimetre. This has been measured and is nearly 4·3 $\times$ 10^{-5} ergs per cu. cm. of space. Thus—

$$\tfrac{1}{2}KV_0^2 = \frac{k}{8\pi} V_0^2 = 4{\cdot}3 \times 10^{-5}$$

and $$V_0 = \sqrt{\frac{4{\cdot}3 \times 8\pi}{k \times 10^5}}.$$

In electrostatic measure $k = 1$, hence $V_0 = 0{\cdot}033$ electrostatic units. Since the *electrostatic unit of pressure* = 300 volts, we have—

$$V_0 = 300 \times 0{\cdot}033 = 9{\cdot}9 \text{ volts per cm.}$$

at right angles to the ray in full sunlight.

To find the maximum current we have—

$$\tfrac{1}{2}Li_0^2 = 4{\cdot}3 \times 10^{-5}.$$

Now $L = 4\pi\mu$, and in electromagnetic

measure $\mu = 1$, therefore $i_0^2 = 4{\cdot}3 \times 10^{-5}/2\pi$, and—

$$i_0 = 26 \text{ milliamperes per sq. cm.}$$

at right angles to the ray in full sunlight.

Thus, knowing the energy passing through unit area in free space, we can determine the voltage gradient and current density in it.

6. Isolated Electric Charges.

The next important property of the ether is that it can take, in two particular cases, a permanent electrical strain. Such a strain constitutes an electric charge and exists in two forms called respectively positive and negative. These "atoms" of electricity are now named *electrons*, though so far the term is given to the negative charge in particular. It is the more easily isolated of the two, and its identification by Sir J. J. Thomson is one of the greatest achievements in physics. Whatever the shape of the positive and negative atoms of electricity may prove to be, it is at least certain that the mode of formation of one is the inverse of that of the other. Yet their properties are so different that we cannot say one is the image of the other as in a mirror.

This would probably be the case if the two units were the same size, but, small as the negative electron is—its diameter is $3{\cdot}7 \times 10^{-13}$ cm., while that of the hydrogen molecule is $2{\cdot}17 \times 10^{-8}$ cm. or 10,000 times larger—the positive unit is still smaller. The charge of an electron is $1{\cdot}57 \times 10^{-19}$ coulomb.

7. Nature and Shape of Electrons.

Before we deal with some of the effects of electrons in motion, let us try to form a picture of their shape and nature. The negative electron is light and mobile. It exists independently of atomic matter, and can slip easily through it. The motion of these electrons through a wire is the electric current. The positive unit is dense, and forms the nuclei of atoms. It will be shown later that all atoms are probably built up of negative electrons in motion around or linked to positive nuclei. The positive charges play no part in current phenomena in wires other than being the fixed or vibrating nuclei of atoms of which the wire is made. An isolated positive charge, if in motion, would set up around the line of advance a right-handed magnetic field. This is the well-known *corkscrew rule*, the

current in a wire being taken to flow in the direction of motion of a positive charge. A negative charge moving in the opposite direction sets up a field in the same direction, as in Fig. 3.

Why should a straight line motion of charge produce a torsional ether strain around it?

FIG. 3.—MAGNETIC FIELDS ESTABLISHED BY MOTION OF ISOLATED POSITIVE AND NEGATIVE CHARGES.

The effects are exactly as if electrons had twists like the fins of a propeller. If a free propeller is drawn through water it rotates like a ship's log. One with right-hand pitch rotates in a right-hand direction, looking in the direction of motion, and rotates the towing line so that if the latter were held it would acquire torsional strain. In the same way such a propeller placed in a liquid having rotational motion only would advance along it like a nut along a bolt. A positive electron, which behaves as if right-handed, moving from left to right, sets up a right-handed magnetic field, Fig. 4, that is, it gives energy

of strain to the surrounding ether, which flies back when the motion ceases. We can regard this twist as located in the ether at the head of the kink as in the towing rope.

In fact, as will be shown later, we can regard the movement of an electric charge in wires as always caused by a tension, as if drawn

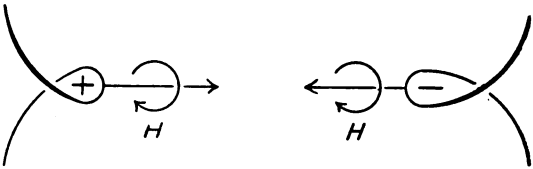

FIG. 4. FIG. 5.
MAGNETIC FIELD AS A TORSIONAL STRAIN ESTABLISHED BY MOVING CHARGES.

along by small local attractions, and not pushed by the external field.

The ether in front of the approaching charge is at rest. The medium has to take up this strain, assumed to be rotational, pass through the identity of the kink as through a vortex, and relax when it has passed. On this view, a magnetic field is a torsional strain around the line of motion, and cannot be imagined apart from moving electric charges.

A negative electron, Fig. 5, moving from right to left also sets up a right-hand twist with

regard to the direction of motion of the positive charge, and is the source of the magnetic field around a current-carrying conductor.

The model of the positive electron can be represented by placing the palms of the hands together, the left hand uppermost, and rotating it clockwise, bending the fingers ; the negative electron is with the right hand uppermost, and rotated anti-clockwise. *Such systems lock* because of the bending of the strained medium in three dimensions, *and are permanent*, if each unit filament has a twist, that is, if the loops of Figs. 4 and 5 are not single cords but made up of many threads, each having a twist. The torsional strain is concentrated at the knot, but spreads out from it into space, so that each element of the surface of an enveloping sphere of large radius has a torsional strain in a plane at right angles to the radius. A right-handed or positive knot would require a right-handed twist of its filaments, a left-handed or negative knot the reverse. A set of cones, forming a spherical field of force expanding from a point, if twisted and placed together, settle down to a mean twist, for the twist of one can only relax by increasing that of its neighbours.

We know from the phenomena of light and electric waves that the ether behaves as if it had enormous rigidity. Thus a steady twist in one direction would cause an expansion of the ether matter, and a steady twist in the other direction would cause a contraction, after the manner of movement of the balance spring of a watch. We know, too, from the phenomena of radioactivity that the positive unit is much denser than the negative. It is then reasonable to suppose that in the negative electron the ether is relaxed so that its density is less, and that a positive electron may be likened to a spring wound up. Either case is a locked system under intense strain.

8. Attraction of Opposite Charges.

The electron structure is three-dimensional, and the strain spreads out so that at large distances from the centre it is nearly uniform over a sphere. Any action of another strain centre which makes the local unsymmetrical strain of such a structure less will result in attraction. The resultant potential energy of two unlike strains is greatest when they are furthest apart; they are, therefore,

forced together. That of two like strain centres is greatest when close together, for the strains add. They, therefore, repel one another, for any elastically strained system in nature relaxes if left to itself, and the charges move so that the resultant strain

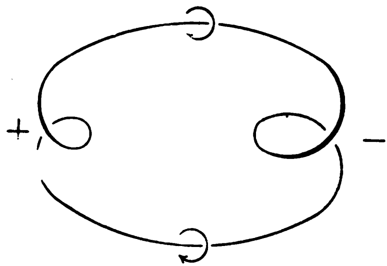

Fig. 6.—Electrostatic Attraction of Opposite Charges.

is a minimum. Repulsion and attraction of electric charges depend on whether their intrinsic strains are of the same or opposite kinds.

The simplest model of electrostatic attraction is Fig. 6. Here the charges are connected by a common strain, and there is no external field. They cannot absolutely combine without destruction of the identity of the electrons. At some point the forces due to the increase of curvature of the strain line would be so

great that its component would balance the force drawing them together. At very short distances apart there is apparent repulsion. At such distances the inverse square law cannot hold, for the essence of that law is that strain spreads out uniformly in every direction over a sphere from a centre of strain.

9. Nature of an Electric Field of Force.

Lines or tubes of force have no identity, though they are convenient for purposes of illustration. All that exists, starting from an electron as a basis, is strain, and the stress associated with it.

A common specification of an electric field of force is the state of the space between two surfaces charged with opposite kinds of electricity, the positive being at higher potential than the negative. How does this fit in with our models of electrons? Imagine the surface of each plate to be covered with twisted centres of strain. They repel one another and, therefore, take positions after the manner shown in Fig. 7. Part of the strain of each electron on one side is used in holding the charge on to the atoms of the plates, and part is carried over, and is common

to both sets of charges. Since each electron is a twist the total effect on unit area of plate is a tube of force having a circular strain, Fig. 8. Seen from the positive plate the strain is right-handed, for the sum of collected

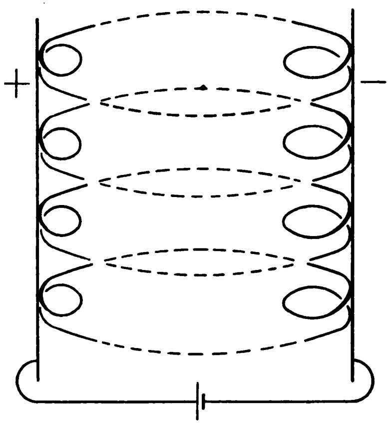

Fig. 7.—Electric Field of Force Between Two Plates.

right-handed strains as in Fig. 4 is right-handed. Seen from the negative end the strain is left-handed.

If the plates are short-circuited by a wire the negative charges move sideways across the plate, rush down the wire and, on meeting the positive charges, form the group of Fig. 6,

attached to some atom, from which the negative electron can break away and wander through the circuit under the influence of the applied electromotive force.

An electrostatic field is, on this view, a steady strain of the ether consisting of a

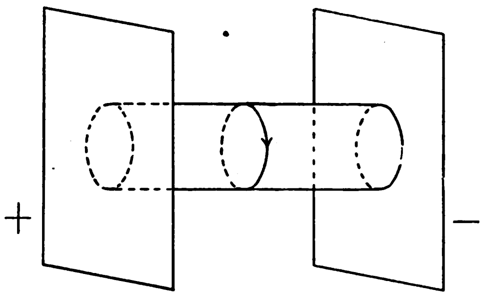

FIG. 8.—TUBE OF ELECTROSTATIC FORCE BETWEEN TWO PLATES.

torsional ether concentration at the positive pole and an expansion at the negative. There is no motion, the field is truly static.

It is proved in text-books that there is a tension along the line of an electric field equal in intensity to $2\pi N^2$, where N is the number of tubes of force per unit area, and a compression equal in intensity at right angles to it.

Lines or tubes of force, therefore, behave as if they were elastic bands in tension and torsion.

10. The Nature of the Field in a Wire.

When a voltage is applied to a wire, lines of strain associated with the electric charges on one battery pole do not stretch further than the nearest molecules of the metal, but these becoming strained, in turn hand on the action across the ether between atoms, and so through the wire to the opposite pole of the battery. A molecule cannot sustain more than a certain amount of electric strain: it becomes electrically saturated. We must imagine the negative electrons being drawn into the positive pole, and so to the chemical elements of the cell, there creating a state of electrical unsatisfaction which is handed on from molecule to molecule, and by which electrons are continually drawn over.

11. Nature of a Magnetic Field of Force.

As stated in §7, when a negative electron is in motion towards a positive pole, it sets up a twist in the ether around its line of movement that is right-handed when looking towards the negative pole. Regarding this

as the magnetic field it is extremely feeble. In a wire carrying one ampere there are 6·36 $\times$ 10^{-18} electrons passing any given point per second, for an ampere is a coulomb per second, and the charge on an electron has been given as 1·57 $\times$ 10^{-19} coulomb, of which the above figure is the reciprocal. Of this great number of electrons—millions of millions of millions—each one adds an equal share to the effect, and we can form, from our experience of the intensity of the magnetic field due to an ampere in a straight wire, some numerical conception of the smallness of the magnetic effect of a single electron moving in the wire as part of the current. Yet the cumulative magnetic effect of electrons in currents of only a few tens of thousands of amperes is sufficient to wreck the greatest generators made.

The electrons are sufficiently far apart not to interfere with one another's action, and their influence is not confined to the wire, but spreads out uniformly, so that doubling the distance from the wire halves the intensity of the magnetic field. In short, the field varies inversely as the distance. In a straight wire, the current being the same everywhere, the field is a cylindrical strain uniform along

the length. It differs entirely from an electrostatic field, and has no influence on a charge at rest in it. It is, however, possible that the magnetic field of a moving electron may have effect on an electron at rest when at distances apart comparable with their own dimensions.

Torsional strain must both open and close the intrinsic ether structure, to account for the elastic vibrations of light. On our hypothesis the negative electron is a left-hand twist and is ether *expanded*. Now when the twist of a cord is slackened it lengthens, and when released it contracts to its original length (experiment with string). Thus when an electron in motion is stopping and its magnetic field strain is going back to its original state, the electron *is drawn forward* in the same direction on the assumption that the torsion is in the ether ahead of the moving charge, as in our model.

The magnetic field which in this way confers on the moving electron the property of momentum therefore causes it to behave as if it had mass.

There is a tension along a magnetic line of force, and a compression at right angles to

it equal to $2\pi N^2$, where N is the number of lines per unit area perpendicular to the field.

12. The Mass of an Electron.

Whether the charge is positive or negative, when in motion under the influence of a field of force, it is either driven forward by the torsion of the field screwing it into the ether matrix, or, when the field is cut off, it is drawn forward by the relaxation of the strain in front of it. We are to suppose that the ether, of which an electron is composed at any instant, does not move forward with it, or the earth, in moving through space, would carry with it an immense volume of ether, and it is known that there is no "ether drag" of measurable magnitude. It is the strain that has identity. Thus each portion of the ether, as it approaches a moving electron, gradually takes up the strain and relaxes as the strain centre passes. The motion of the negative electron is easier, for on our hypothesis it is relatively large and open, and its strain is taken up over a larger region. The positive electron being small and dense, it is difficult, as it moves, for the normal ether to take up the intense strain quickly. The

positive electron thus behaves as having greater inertia or more mass, for the intensity of torsion at its head is greater, though since the charges are equal the total energy of strain is the same for both units.

The kinetic energy of a moving body is $\frac{1}{2}mv^2$. This can be measured by observing, when a target is struck, the rise of temperature of the whole. The energy of electrons in motion has been determined in this way by observing the temperature rise of a metal cup bombarded by discharge from hot wires in a strong field. The particles in such a discharge have an ordinary mass m_0 and an electromagnetic mass m, that is, an apparent mass conferred on the particle by the self-induction of the charge carried by it. The ratio of m_0 to m has been calculated by Heaviside and Sir J. J. Thomson, and it has been observed by Kaufmann, and the conclusion from comparison of theory and experiment is that the inertia of matter is due entirely to the self-induction of the electric charges of which it is composed. This being so, there is no mass or matter apart from electric charge and, when reduced to its elements, there is nothing but ether and electricity in the universe.

13. Constitution of the Atom from Electrons.

In order to see how the electron theory explains the conductivity of metals, let us consider how atoms are built up of electrons. The investigations of Sir J. J. Thomson, Sir Ernest Rutherford, and Professor Bohr of Copenhagen have given strong evidence that the most elementary atoms are flat. They consist of negative electrons grouped around positive electrons as nuclei. The number of units of charge forming the nucleus is very nearly the same as its "atomic number," or place in the scale of numbers connecting atomic weight and X-ray spectra found by Moseley. In this remarkable series each element advances by unity, hydrogen 1, helium 2, lithium 3, up to uranium 92, exactly their place on the list of elements, and it has been suggested that these numbers represent the magnitudes of the nuclear charges. If so the mass of the positive electron must be capable of small variations, for the mass of an atom is located in the positive nucleus, and should, therefore, change by integral steps, which the atomic weights do not. Moreover, Nicholson has shown that there are

in nebulae elements having lower nuclear charges than hydrogen.

The mass of the negative electron varies with its speed of *motion*. Why should not that of the positive electron vary with its *strain*? For example, a positive charge at rest has a certain mean angle of twist. If now by the grouping of its associated electrons in an atom this is increased, the loop or knot of the twist (Fig. 4) is tightened, and the mass can be conceived to be greater, since the difference between positive and negative is, on our model, attributed to whether the normal ether is strained denser or rarer. In the same way, if the twist is forced open, its effective mass may be less. The variations, in any case, can only be small in a body with such high intrinsic strain.

According to our model we may represent a negatively charged unit by Fig. 9 (A). Hydrogen is electropositive, and normally monovalent. It might then be denoted by Fig. 9 (B) with two positive nuclei. This would bring it into line with certain of the higher elements, since the atomic number of many of them is equal to half the atomic weight.

In Fig. 9 (A), half the charge of the positive nucleus is taken as linked with half that of one electron; and, since the charges on the positive and negative electrons are equal, there is left spreading out into space a strain

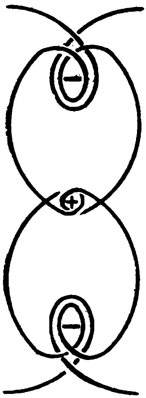

Fig. 9 (A).

Negatively-charged Unit.

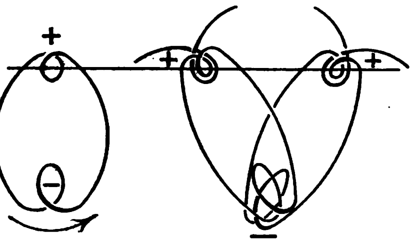

Fig. 9 (B).

Positively-charged Unit.

equal to that produced by a single negative charge. The negative electrons are free to rotate about the positive nucleus, and to vibrate.

In Fig. 9 (B), in order that the positive nuclei should be at rest, they are placed on an axis about which the single negative charge

rotates, and there is now a strain equal to that of one positive charge spreading out into space.

Elements which have no valency, i.e. do not combine with any other kind of element,

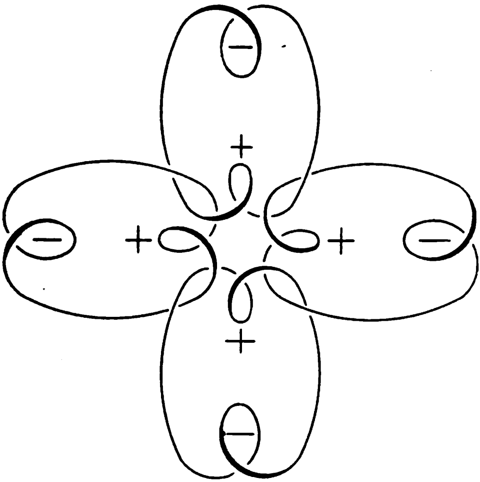

FIG. 10.—DIAGRAM REPRESENTING AN ATOM.

would then be represented by groups of Fig. 6 linked as in Fig. 10. The extension of this model to the constitution of the higher elements is beyond the subject of these lectures. The point essential to the theory of conductivity is that a negative electron can be

unlooped from a molecule under the influence of collision, or possibly, in massive elements, be driven into the molecule by the same process. The electron may even be on our model so wide a loop that it can become attached to a molecule by the simple process of being strung upon the molecular line of strain (Fig. 11), and the energy required for

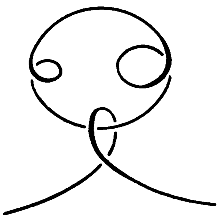

FIG. 11.—REPRESENTING THE POSSIBLE ATTACHMENT OF AN ELECTRON TO AN ATOM.

ionization is then that necessary to tear such a unit through the interlacing bond. In good conductors such a process is exceedingly easy. In insulators there are no free electrons, though there are mobile or valency electrons in the atoms of such materials.

Atoms are held together to form molecules by electrical forces or bonds, represented in the above figures by lines of strain. One of the most important constituents of organic

insulating materials is the carbon atom. This is known to have four axes of symmetry like those of a tetrahedron, and it is suggested here that it has six nuclear charges, each of two positive units. The combinations of this atom with hydrogen to form the hydro-

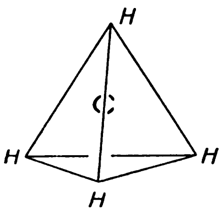

FIG. 12.
METHANE (CH_4).

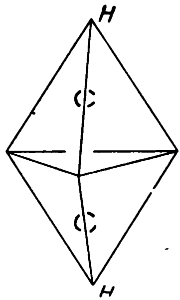

FIG. 13.
ACETYLENE (C_2H_2).

carbons, of which oils and paraffins are composed, are the most useful insulating materials for electrical engineering purposes. Methane (CH_4), one of the gaseous paraffins, is represented by Fig. 12, a carbon atom with four hydrogen atoms symmetrically around it. Acetylene (C_2H_2) is represented by two such pyramids (Fig. 13), having hydrogen atoms at the two opposite points. Langmuir has given, in the *General Electric Review*, July and August,

1919, an extremely interesting theory of these atomic structures.

In solids, at normal temperatures, these molecules vibrate elastically about fixed positions. When the solid is heated the vibration is more violent and, when the heating is continued, the molecular groups shake themselves loose and form liquids, or disintegrate into vapour.

14. Conductors and Insulators.

All the foregoing leads to consideration of the nature of conductors and insulators. When an insulating material, or *dielectric*, as it is called, is placed in an electric field the electrical units of which it is composed are forced apart. In the most elementary case Fig. 6 is strained elastically, as in Fig. 14, from the full to the dotted positions. If the original form were a sphere it would become an ellipsoid. On the removal of the field a single unit, thus strained elastically, would recover its original shape with the velocity of light in the medium; but when there are many such elements closely packed together one influences another, by reason of their mutual attractions and repulsions, so that they cannot recover so

quickly. This is the origin of the *residual charge* in condensers, the magnitude of which is proportional to the initial distortion, that is to the applied field. Such a state of distortion is called *polarization*; a perfect insulator polarizes but will not pass a steady current.

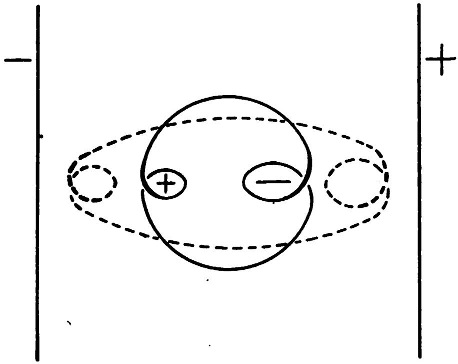

FIG. 14.—ELASTIC STRAIN OF DIELECTRIC IN ELECTRIC FIELD.

Conductors have the same general form of atomic structure except that they are usually much denser. Partly because of this, and the consequent increase of the intermolecular fields, electrons can more easily pass from one to another molecule under the influence of an applied voltage. The force with which an electron is held to a molecule is not sufficient

to retain it for more than a moment when a current is flowing. The current in a wire consists of a stream of these electrons, the numbers of which have been given previously (§11).

While moving onward as a stream, these electrons are darting to and fro continually, so that they follow the law of a gas. They are, in fact, a form of etherial gas enclosed in the metal, having a "temperature" due to their energy of bombardment acquired in the field in equilibrium with that of the molecules of the wire. The surface of the metal has a kind of electrical surface tension which prevents the electrons from escaping until the temperature is raised to such a point that they are driven off like sparks from hot iron. This *thermionic discharge*, as it is called, is of the greatest engineering importance, for the *valves* used in wireless telegraphy and telephony depend for their action upon the ionic discharge from hot wires in vacuo.

In the electron stream through wires the positive electrons play no part, they are the nuclei of the atoms, and are held in position by the fixed negative electrons which form

part of the atomic structure. On these lines, thinking only of the movement of electrons, Ohm's law can be proved,* with its immediate consequence that the heat generated in a conductor per second is ri^2.

15. Thermal Conductivity.

The conduction of heat through solid bodies is of two distinct kinds: through conductors in which electrons convey part of the heat, and through insulators, such as ebonite or cork, where they do not. In the one case, heat is transmitted electrically, and it can be shown that $k = Anlu/3$; where l is the length of the free path of an electron, n the number of electrons in unit cube, u the velocity of electrons in the conductor, A a constant, and k the conductivity. (See Campbell's *Modern Electric Theory.*)

In insulators there are no free electrons. Heat is there transmitted by molecular vibrations, as shown by the fact that the conductivity of many substances when solid is given by the relation $k = E\rho = V^2\rho^2$; where E is

* See the chapter on Electrical and Thermal Conductivity in *Modern Electric Theory*, by N. Campbell (Cambridge University Press); also *The Electron Theory of Matter*, by O. Richardson (Cambridge University Press).

Young's modulus of elasticity, ρ the density, and V the velocity of sound in the body. This rule gives a means of determining the thermal conductivity of certain materials, such as sulphur or ebonite, by measuring the note which a bar of it emits when tapped. On the electric theory of matter elasticity also is electric. It is a measure of the cumulative forces holding matter together, the mutual influence of groups of electric charges on adjacent groups.

16. Electrical Conductivity of Metals and Influence of Temperature.

Assuming that electrons collide only with atoms and not with one another, the electrical conductivity can be shown to be—

$$\sigma = \frac{A\,l u\,n}{T},$$

where n, l, and u have the same meaning as before, A is a constant and T is the absolute temperature. Thus at the absolute zero of temperature, $-273{\cdot}3°$ C., a pure metal wire should have no resistance. It has recently been shown by Prof. Onnes, of Leyden in Holland, that this is actually the case a little above zero.

The resistivity ρ is the reciprocal of the conductivity σ, and, substituting $1/\rho$ for σ in the above expression, we have the ratio ρ/T is constant, leading directly to the relation

$$\rho_1 = \rho_0 \left\{1 + a(T_1 - T_0)\right\}$$

where a is the temperature coefficient of the metal, and ρ_1, ρ_0 the resistivities at T_1, T_0, respectively.

The reason, therefore, why efficiency of transmission is not perfect is that electrons driven through the wire under the influence of the voltage applied to its ends, and acquiring kinetic energy in the same way that a falling stone acquires it, give up their energy to atoms with which they collide, just as a target is heated by the impact of a bullet. The motion of the electron is thus checked. At or near zero temperature, however, matter becomes so rigid that collisions of electrons cannot set the atoms in motion; the collisions are perfectly smooth, and no energy is lost. In other words, the metal becomes a perfect conductor.

17. Proof of the Right-hand Law of Generation of Electromotive Force in a Magnetic Field.

Before we consider ionization in gases it is appropriate here to give a proof of this

well-known law. We have said before (§7) that there is a magnetic field around a current, the direction of which is related to that of the current as the direction of twist of a corkscrew is to the direction of motion of the point—right-handed when screwing in, left-handed

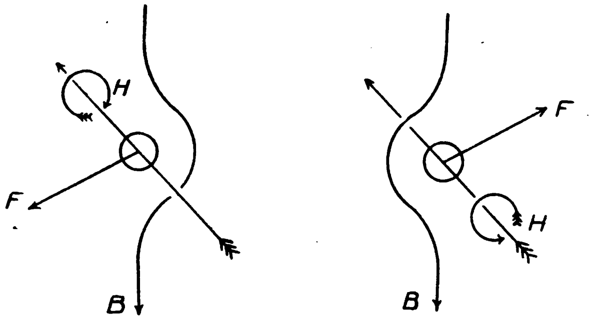

Fig. 15.—Force on Positive (Left) and Negative (Right) Charges Moving Through a Magnetic Field, *B*.

when screwing out. If all matter is composed of electric charges, and a charge in motion is a current, it is clear that there should be some action between matter and a magnetic field through which it is moved. Assume a positive charge to be moving, as shown in Fig. 15, through a field denoted by B. The field will be distorted by the circular field H around the line of motion, and there will be

a force on the charge in the direction *F*. In the case of a negative charge the force is reversed.

Suppose, now, we have an uncharged cube of matter of any kind, which on the preceding theory contains an equal number of positive and negative charges or electrons. Any movement of the cube will cause each electron to act as forming a minute current, but the total magnetic effect will be zero, since the positive and negative charges are equal in number. When the movement is in a magnetic field the result is not the same. There is a force on the positive charge in one direction, and on the negative charge in the opposite direction. If it is a *non-conductor*, the cube is polarized as shown in Fig. 16. The front face becomes charged positively, and the back face negatively. The lines of force bent over the front are caused to do so by the motion of the negative charge and this is, therefore, driven to the back. In the same way the positive charge is forced to the front. $F+$ and $F-$ are equal and opposite, the charges on the faces are, therefore, equal and opposite in an insulator.

In a *conductor* the positive charge moves

slightly as in an insulator under its elastic attachment to the atomic structure, but it cannot move continuously. It is anchored into the structure. The negative charge is

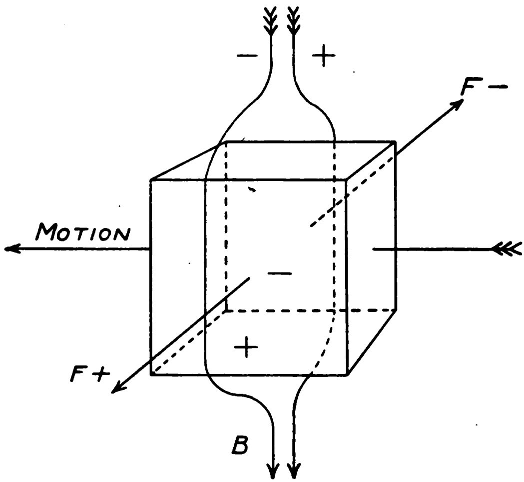

FIG. 16.—POLARIZATION OF NON-CONDUCTING CUBE BY MOTION IN MAGNETIC FIELD.

attached so lightly that the least force causes the electrons to stream in the direction $F-$. When the faces of the cube are joined by an external wire, to form a closed circuit, there is a steady stream of *negative* electrons from the negative face through the wire to the

positive face and through the cube, the positive charge remaining at rest.

When we say that a current flows from the positive to the negative end of a wire it is on the convention that the direction of current is that of the movement of the positive charge *if it were free to move.* As we have seen, a negative charge flowing in the opposite direction to a positive charge causes a magnetic field in the same direction. Since the magnetic effect is the most important property of current flow in the transmission of energy, it makes no difference for engineering purposes how the electric charge moves within the wire, but the facts are as stated.

The force on a current i in a magnetic field B is proportional both to i and to B and, when i is in c.g.s. units (amperes $\div$ 10) and B in lines per sq. cm., $F = Bi$ dynes per cm. length of the conductor; or if the length is l cm.—

$$F = B\,i\,l \text{ dynes.}$$

18. Proof of the Law $E = \frac{dN}{dt}$.

Consider an element of a conductor moving sideways with velocity v in a magnetic field

of B flux density (Fig. 17). The number of lines cut in moving a distance s is Bs. The force F on this element is Bi, where i is the current that is equivalent to the movement of the free electric charge q in the element of

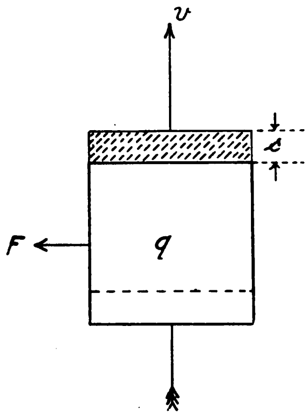

FIG. 17.—ELEMENT OF CONDUCTOR MOVING SIDEWAYS IN MAGNETIC FIELD.

the conductor. It is, therefore, equal to $q\,v$; hence, $i = qs/t$, so that $F = Bqs/t$. But Bs is the number N of lines cut, and by definition an electric field E is the force on unit charge. Hence—

$$F = \frac{qN}{t} \text{ and } E = \frac{F}{q} = \frac{N}{t}.$$

If the field is not uniform or steady, or if the speed is varying, it is necessary to take infinitely small intervals of time and write $E = \frac{dN}{dt}$.

This is the key relation of electrical machinery connecting electricity and magnetism, and its experimental discovery by Faraday was one of the greatest steps in the advance of science.

19. Ionization.

When an electric charge is no longer isolated but is attached to a molecule or group of molecules it forms an *ion*. This word, derived from the Greek verb *to go*, was used by Faraday to denote a charged body of molecular dimensions travelling under electric forces, and playing an important part in the chemical phenomena of liquids, such as electrolysis. Oxygen carries a negative charge, moves to the positive pole, and is termed electronegative. Hydrogen carries a positive charge, and is called electropositive. A negative charge taken from an uncharged molecular group makes the latter a positive ion. When there is a negative unit in excess the ion is negative.

In conducting liquids there are no free electrons, but there are free ions; in metals there are free electrons, but no ions. This is the chief distinction between liquid and metallic conduction.

20. Ionization in Gases.

In a gas between two charged surfaces the few ions that are always present are multiplied by the process called "ionization by collision." The force exerted by the field of intensity X on a unit of charge e is Xe, whatever the mass of the ion may be. Under the influence of this force the ions begin to move, and as they acquire velocity their kinetic energy increases. They eventually collide with an un-ionized molecule and, if their energy is sufficient, throw it into such violent vibration that an electron is thrown out of its structure. In radio-activity an atom may pass through a molecule and tear out an electron on the way. However formed, once a molecule is ionized, it acquires energy in the field, and produces another by collision. The process is one of compound interest. Both positive and negative ions are produced simultaneously, and these begin to recombine. The number of

ions at any point in space is the difference of the two kinds which have been produced in reaching the point and have not recombined. The subject is dealt with in Sir J. J. Thomson's book *The Conduction of Electricity in Gases*, and later in Prof. Townsend's *Electricity in Gases*. The expression given by the latter for the number n of ions produced, when there were originally n_0 ions at the negative electrode, which reach the positive electrode a centimetres distant is—

$$n = \frac{n_0 (\alpha - \beta) \varepsilon^{(\alpha - \beta)a}}{\alpha - \beta \varepsilon^{(\alpha - \beta)a}}$$

One consequence of this relation is of the greatest interest in the transmission of electrical energy. When the denominator is zero n is infinite, that is, there is a continuous bridge of electrification between the poles and a spark passes. n is infinite when—

$$\alpha = \beta \varepsilon^{(\alpha - \beta)S}$$

where S is the sparking distance. Here $(\alpha - \beta)S = \log (\alpha/\beta)$, or $S = \dfrac{\log (\alpha/\beta)}{\alpha - \beta}$, and if X is the sparking voltage gradient, in volts per centimetre, $V = SX$. Many measurements have been made of the electric strength of air,

and they agree closely with the above expressions, the proofs of which may be found in Townsend's book.

Steinmetz also gives as an approximate expression for the sparking distance in air between plates $S = AV + BV^2$; where A and B are constants determined by experiment.

21. Brush and Corona Discharges.

The luminous glow observed at points or along wires at very high voltages are cases of ionization by collision. The glow at the negative point is caused by the intense outward acceleration of the ions there and their violence of collision, which sets the electrons of the atomic structure of the gas vibrating, and, therefore, gives rise to radiation as light. At the positive point the glow may be caused by an equally intense violence of collision of negative ions approaching the point. These discharges take energy from the line which increases suddenly when the glow begins.

22. Design of High Tension Insulators.

In an ordinary plain insulator, as shown in Fig. 18, the main electrostatic field is in the

body of the porcelain, as indicated by the dotted lines. The object of the long spread or fin is certainly not, as is often supposed, for the purpose of keeping off moisture, as in any sudden rise of air temperature there is always moisture deposited on a colder insulator. Particles of moisture in the form

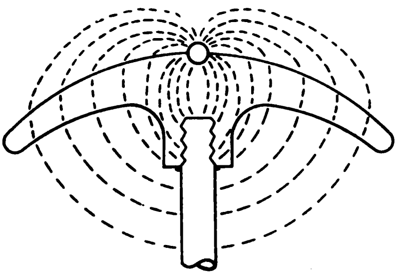

FIG. 18.—ELECTROSTATIC FIELD IN PIN-TYPE INSULATOR.

of mist are attracted towards it by the electrostatic field. If the atmosphere were perfectly dry we should rarely get a flash over. Owing to the fact that the atmosphere in this country is never perfectly dry, it is not possible to work at such high pressure as in California, for instance. A pressure of 100,000 volts is not thought to be feasible here for overhead work.

The moment particles of moisture approach

an insulator they are charged by induction; they are then attracted to the solid, and begin to condense on its surface around the top and underneath. The main field, however, is confined to the body of the insulator, and there is little or no field at the tips of the spread, consequently the moisture is not attracted to these parts, and there is less condensation. There is then a break in the surface-conduction path. The reason why insulators are constructed with a large spread is so that *their edges shall always be in a weak electrostatic field.* If, at the same time, sufficient moisture collected slowly to form a conduction path, the water would be dried off by the leakage heating effects, whilst if condensation takes place in an alternating current system, the moisture is, in addition, rapidly dried off by the fanning action of the field.

It should be pointed out here that it is not the moisture itself which is the objectionable feature—pure water being an excellent insulator—but the dirt contained or dissolved in it from the atmosphere.

The *fanning action* referred to above is illustrated by the following experiment. Referring to Fig. 19, a loop of tungsten wire connected

in a direct current circuit is placed round the outside of a quartz tube, which is closed at one end. The direct current circuit contains an adjustable resistance so that the current can be regulated to the amount required to raise the tungsten wire to a red heat. Inside the quartz tube is a copper rod forming one

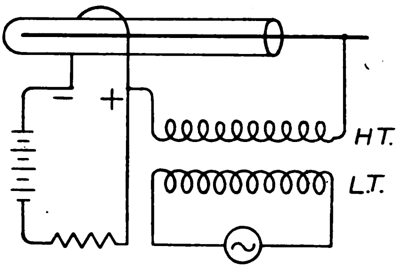

FIG. 19.—ILLUSTRATING FANNING ACTION OF ALTERNATING ELECTROSTATIC FIELD.

terminal of a 7,000 volt alternating current circuit, obtained from the high tension side of a small transformer, the other terminal of which is connected to one of the battery leads. Owing to the insulation of the quartz tube there is no connection between the alternating and direct current circuits except electrostatically. With only the direct current circuit closed the tungsten wire glowed brightly; but when the alternating current

circuit was closed, the wire darkened, leaving only a faintly visible blue discharge. This effect is due to the fact that with the alternating current circuit closed the molecules of air near the wire become ionized by the corona due to the high voltage, and are attracted and repelled as the voltage alternates, the resulting fanning action of the ions being so great as to cool the wire to blackness.

This same fanning action takes place on an insulator carrying alternating current, and any moisture is quickly dried thereby. When sufficient moisture accumulates to permit of a trickle of alternating current passing over the surface of the insulator, the moisture is dried off by the heating effect of the I^2R losses. The total leakage current may be a perceptible part of the line current.

23. Underground Cables.

Consider first the insulation of cables. All solid insulators, such as vulcanized indiarubber, were shown first by Kapp to obey with great accuracy the law—

$$S = AV + BV^2$$

where S is sparking distance, V sparking voltage, and A and B constants for the material.

Paraffin wax is a perfect insulator, and is a modification of the above rule, in that the first term is absent.

A number of values for A and B were worked out in the *Philosophical Magazine*, Vol. XXX, July, 1915, from which the following are taken—

V.I.R. Cable, $A = 5{\cdot}16 \times 10^{-6}$ and $B = 3{\cdot}19 \times 10^{-10}$.

Porcelain, $A = 7{\cdot}7 \times 10^{-6}$ and $B = 0{\cdot}34 \times 10^{-10}$.

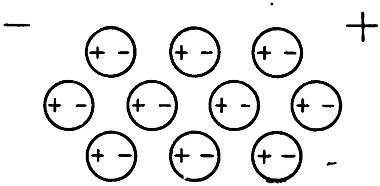

FIG. 20.—CHAIN OF POLARIZED MOLECULES IN INSULATING SUBSTANCE.

Let us consider how a failure takes place in a solid insulator. It cannot take place by ionization, as there are no free ions in an insulator, neither are there any free electrons. The only feasible explanation at present is that when we have a chain of molecules of substance polarized as shown in Fig. 20, each molecule is subject not only to the applied field, but also to the electric forces of adjoining

molecules. So highly are the molecules keyed up, that when one pair of charges combines there is a slip of charge all along the line of strain on which failure begins. This is on the lines of the electrolytic theory of dielectrics suggested by Prof. Chattock in 1892.

24. Grading of Cables.

Suppose we have a cable surrounded by a sheath or immersed in water; the lines of stress in the dielectric are not equally concentrated everywhere, the part of the dielectric nearest the conductor being electrically strained to a greater extent than the outer portion. The voltage gradient through the thickness of dielectric $= V_1 = q/k$ in dynes on unit charge. In terms of lines or tubes of force per unit area at radius r,

$$V_1 = \frac{4\pi q}{(2\pi r)k},$$

where q and k are the charge per unit length and dielectric constant.

To obtain perfectly uniform grading V_1 must be a constant, that is, kr must also be constant. We require, therefore, the greatest dielectric constant at the smallest radius.

25. Dielectric Heating.

In a perfect dielectric the displacement q would be proportional to the voltage, but dielectrics are always more or less imperfect. The curve of dielectric polarization for a perfect material would be simply a straight inclined line indicating no loss of energy (see Fig. 21). In the case of paraffin, which approaches perfection, the curve of dielectric loss is a narrow, straight-sided loop (Fig. 22). This form of flat-sided curve is quite satisfactory to find in tests as it clearly indicates that there is no conduction current.

If, however, the hysteresis curve begins to assume an oval shape (Fig. 23) it is a sure sign that there is water present, as the curving of the sides is due to conduction current, and in the case of a perfect conductor the curve would be a circle.

26. Electrical Endosmose or Osmosis.

Moisture lowers the dielectric strength and increases the dielectric constant in all cables, even in gutta-percha, which is the only insulating substance which appears to withstand sea-water for any length of time and prevents its

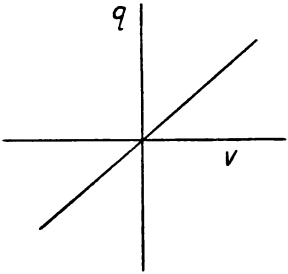

Fig. 21.—Dielectric Polarization for Perfect Insulator.

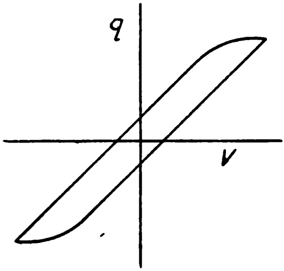

Fig. 22.—Dielectric Polarization Loop for Paraffin.

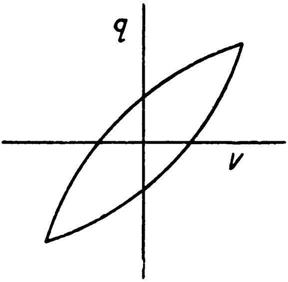

Fig. 23.—Unsatisfactory Curve of Dielectric Hysteresis, Indicating Presence of Moisture.

penetration. Indiarubber is not impervious to moisture, and, therefore, cannot be used permanently under such circumstances.

If there is a small fault on an underground alternating current cable due to moisture, it will as likely as not be self-curing, but on a direct current cable such a fault is almost invariably cumulative, since moisture is driven in the direction of the current by the process called electrical endosmose. There is no accepted theory at present to explain why water should move in this way, but it is possible to suggest a solution.

A pure insulator will not exhibit endosmose; pure water, for instance, will not. The moisture with which we are concerned is not pure, but is slightly conductive, and exhibits the effects of osmosis when contained in a thin film or tube.

When a thin film of water lies between two flat plates and the terminals of a direct current circuit are introduced into the extreme ends of the water, then if there are ions present they will be acted upon by the field produced, the positive or hydrogen type being forced towards the negative terminal, whilst the negative or oxygen ions are forced towards the positive terminal (Fig. 24).

The force acting upon these ions will be $F = Xe$, where $X =$ the intensity of the field in volts per centimetre. The force $F =$ mass $\times$ acceleration, therefore, $ma = Xe$. The charge e is the same for both positive and negative streams, two hydrogen ions carrying the same charge as one oxygen ion, but the acceleration of the atoms is not equal.

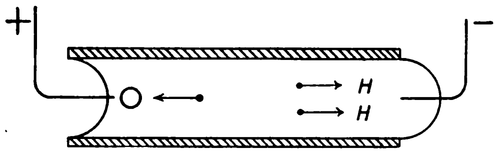

FIG. 24.—FLOW OF IONS IN FILM OF WATER.

Assuming the charge to be carried by groups equivalent to the atoms of each, the acceleration $a = Xe/m$, that of the hydrogen $= Xe/2$, and of the oxygen $Xe/16$. The ratio of the acceleration of the hydrogen to that of the oxygen is thus $8:1$. The hydrogen ion accelerates more rapidly and the liquid moves as a whole in the direction of the hydrogen ions—that is, from positive to negative through the liquid.

It is, for some unknown reason, easier for water to penetrate bitumen than indiarubber.

Indiarubber is a recent vegetable gum, bitumen a much older chemical formation with the resins broken down.

When two cables of opposite polarity are in moist earth there is an electrostatic field between them unless the cables are sheathed or where the sheath is broken; and if there is a slight crack by which it can enter, water is forced into the negative cable. This may go on until there is a balloon formed. A surgical operation must then be performed, and the water drained off, when the sac will usually subside and the cable can be mended.

It is one of the advantages of alternating current transmission that there is no electrical osmosis. A faulty underground system can be cured by changing from direct to alternating current working. In one such case the faults on an underground cable system were reduced from 160 a year on direct current to 1 on alternating current four years after the change was made, and with the same cables in use.

27. Energy Paths.

Next to Faraday's discoveries the work that has perhaps been most fruitful in the development of electricity—both in theory and practice

—is Maxwell's theory of electromagnetic waves in space, the famous Chapter 20 of his great treatise published in 1873. The experimental confirmation of this by Hertz and Lodge gave rise to modern wireless telegraphy. The conception of the transmission of energy through space is now familiar to us all, but the mode

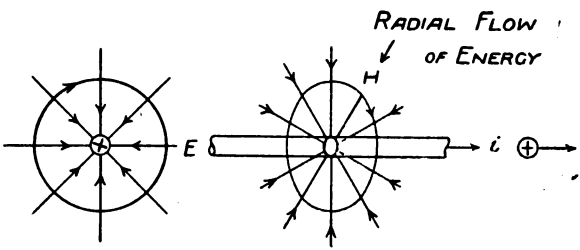

FIG. 25.—CONCENTRIC MAGNETIC FIELD AND RADIAL FLOW OF ENERGY.

of transfer of energy, the energy path, which was discovered by Poynting in 1886, is not so well known. Poynting found that the flow of energy was always at right angles to the direction of both the electric and magnetic fields. In the case of a wire carrying a current, for example, the electric field, that is, the voltage gradient, is along the wire, and the magnetic field set up by the current is in circles in a plane at right angles to it (Fig. 25).

The energy, therefore, streams in from the strained space around the wire. This strain is of two kinds: (i) the voltage or electrostatic field, attempting to break down the dielectric, which is independent of whether current is flowing or not; and (ii) the magnetic rotational field directly proportional to the current and independent of the line voltage.

The *transmission of energy* is to be considered in two parts, that which is delivered to the motor at the far end of the line, and that which is lost in the line itself. If the wire had no resistance the latter would, of course, be nil. How is energy handed on from one end of the line to the other? Work is always equal to the product of force and displacement. The force is obviously the voltage, the displacement is quantity of electricity transferred. This electricity is negative in sign, and is equal to the product of N, the number of electrons moved, and their charge e. Thus—

$$W = Vq = VNe.$$

The current $i = q/t$, and W is more usually written Vit watt-seconds or kilowatt-hours delivered. To each of the electrons there are two lines of strain (Fig. 6), which stretch

out at right angles to the wire through the insulation, straining it, and end on the nearest charged conductor, which may be the earth. As the electrons move along the wire under the influence of the applied voltage this radial strain moves with it. If there were no strain in the insulation no energy would be transmitted. The transmission of energy, therefore, takes place not in the wire, though the wire guides it, but *in the insulation around it.*

Just as in mechanical engineering it is the member that is strained that breaks down, so here failure of the insulation stops performance. The line insulation transmits laterally the electrical tension from the generator to the motor.

Consider next the *loss of energy in the line.* This is caused, as we have seen, by the electrons colliding with the atomic structure, and delivering it to the energy Xel acquired in being driven by a field X volts per centimetre through a free length l between collisions, e being the electronic charge. This transference of kinetic energy to heat has to be made good by supply from outside the wire, and it is here that Poynting's law makes things clear. The energy enters through the insulation in a

radial direction, and is a slip of strain from it into the wire.

Poynting proved that the energy entering unit area of the surface of the wire per second is, with the above symbols, $XH/4\pi$. The magnetic field H at the circumference of a wire of radius a is $2i/a$, and the resistance of unit length is $\rho/\pi a^2$; X the voltage drop is therefore $\rho i/\pi a^2$, and the energy dissipated is $\rho i^2/\pi a^2$.

But $\dfrac{XH}{4\pi} \times 2\pi a$ is the Poynting flux W into unit length of wire through the surface $2\pi a$.

Therefore $W = \dfrac{1}{4\pi} \cdot \dfrac{\rho i}{\pi a^2} \cdot \dfrac{2i}{a} \cdot 2\pi a = \dfrac{\rho i^2}{\pi a^2}$.

The energy entering sideways through the insulation is then equal to that dissipated by resistance.

This energy is not fed into the end of the wire. The white hot filament of a lamp is able to be uniformly at the same temperature because its energy is supplied uniformly all along its length by the relaxation of strain in the space around the wire. If it had all to be pumped in from an end the parts of the wire nearest that end would be much hotter than the middle portion, and this is not the case. The wire itself acts as a sink of electrical

energy, or as a converter, changing it into the form of heat.

28. The Flow of Energy in Generators and Motors.

Let us consider next the path by which energy is transferred from the engine to the generator windings, line, motor windings and shaft.

We have shown (in Fig. 16) that when a wire is moved through a magnetic field there is an electric polarization of the metal: one end of it becomes positive, and the other negative. The strain of this polarization is in the ether around the electrons in the wire, and in the space around it. On closing the circuit a current flows which sets up a magnetic strain, which in accordance with our model we have taken as a rotation untwisting the ether structure. The resultant of the circular magnetic field about the current in the windings and the straight permanent field of the machine is a field of force represented by Fig. 26.

Now, we have said that there is a tension along each of these lines, as in a stretched elastic band, hence the influence of such distortion is a force in the direction F.

As the wire cuts through the field in the

direction *M* the lines pass into the wire, and move away with less energy of strain than they had, for the lines to the right of the wire in Fig. 26* are more bent than those to the left. There is an electrostatic field along the wire

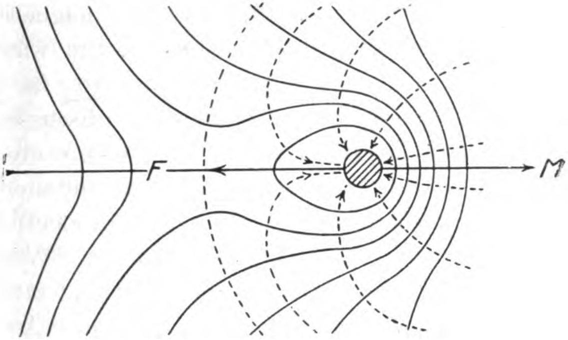

FIG. 26.—RESULTANT FIELD ROUND GENERATOR CONDUCTOR AND LINES OF ENERGY FLOW INTO THE WIRE.

and a magnetic field around it. Energy, therefore, pours into the wire at right angles to the magnetic field, in the plane of the paper, as shown dotted in the figure, and is converted into electrostatic energy of strain in and about the wire. It will be seen that the energy does not enter equally in all directions.

* Based on a similar diagram in Clerk Maxwell's *Electricity*, by permission of the syndics of the University Press, Oxford.

If it did there would be no resultant transverse force on the wire. This electrostatic strain is handed on to the insulation of the line, and is the means by which energy is transmitted to the motor. If it is wished to follow this closer, we must imagine the magnetic field relaxing as it passes through the wire, and so forcing the electrons onward, in a manner similar to self-induction (discussed in §11). If the transmission line is connected directly to the terminals of the generator there is no electric break in the generator of electromotive force or electrostatic stress. With a transformer there is another transfer of electric to magnetic strain and back to electric. Any loss of energy in a line or cable due to resistance is supplied by the relatively slow flow of energy radially into it; if there is none the insulation around the cable carries a flow of energy of strain moving sideways. The direction of flow of electrostatic energy is parallel to the wire; when there is loss in the cable, the line of energy flow converges slowly upon it.

Consider next the *motor*. The current flows through the windings and distorts the field in a direction opposite to that of Fig. 26. The force on the conductor is then to the right,

and the wires move in that direction. The flow of energy is as before at right angles to the lines of magnetic force, and is not symmetrical. The lines of magnetic force are now pulled back by the current, and move through the latter in the same direction as before. The electrostatic field is then in the same direction in space as in the generator, so that the two, being in the same circuit, are in opposition. The conversion of energy is here from the electrostatic field in and about the wire to energy of distortion of the magnetic field, causing a force on the armature conductors which is released by the motion. The energy is transferred to the motor shaft as the latter rotates.

29. The Energy Path in a Transformer.

In the case of a transformer (Fig. 27) the electrostatic energy of the line is carried into the windings. The current in these now sets up a magnetic field which runs in a straight line through the coils. The energy path, at right angles to the wires and the core flux, enters the primary coil radially or at right angles to it at every point under the primary windings as at *A*.

At the secondary coil, the direction of flow of energy is outward from the core to the coil in a direction normal to the core, as at *B*, the reason for the reversal being that, in space, the currents in primary and secondary are in the same direction as shown, while the magnetic flux, passing up one limb and down the

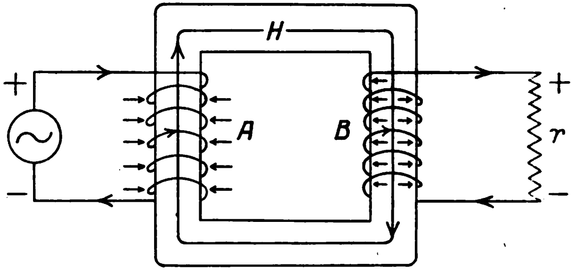

FIG. 27.—ENERGY PATHS IN A TRANSFORMER.

other, is reversed. This electric energy passes along the insulation to the load *r*, where it is converted into heat uniformly over the length of the resistance wire.

30. Energy Paths in an Induction Motor.

The stator windings of an induction motor receive electrostatic energy from the line, and convert it into magnetic energy by the process we have outlined, of a radial displacement

entering the wire and acting on the electrons. The electrons are accelerated and, on our hypothesis, given a twist which by their rigid strain is handed on to the ether as the magnetic field in the iron. This magnetic strain is linked with the rotor winding, and relaxing there produces in the rotor wires a linear electrostatic field on the electrons, setting up a current when the rotor circuit is closed. The reaction of this current on the common field distorts it elastically, and the mechanical strain is handed on to the rotor wires, which are shot forward like an arrow from a bow. The final form of the energy is a force on the rotor wires with a displacement in the direction of the force which, in the case of an ideal motor with perfect efficiency, is equal to the energy transmitted by electrostatic strain along the cable to the machine.

31. Single Travelling Waves on a Line.

Any sudden change in the electrostatic state of the line such as a momentary short circuit, or a lightning discharge, gives rise to single travelling waves. These usually have a steep wave front and tail away behind, as in Fig. 28. A single isolated wave of this

kind may arise on any line. If the line is struck by a lightning discharge between the ends there are two such waves moving in opposite directions from the point of attack. Such a wave is a true *surge*, though this term is generally applied in engineering to the effects of a sudden arc or load of longer duration

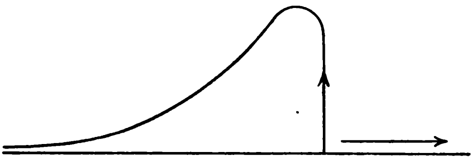

FIG. 28.—SINGLE TRAVELLING WAVE WITH STEEP FRONT.

than the above. The electrostatic stress denoted by the curve is in the end spread uniformly along the line. A surge here is a transient local voltage superposed on the line pressure. It will be dealt with numerically later.

32. Reflected Waves.

Wherever the capacity or inductance of the line changes suddenly there is reflection of single waves, or of rapidly varying waves which are in trains or groups. The pressure

piles up at the ends and starts the surge back along the line. Where two such impulses meet by reflection from opposite ends of a line there is great danger of insulation breaking down from the three superposed pressures (see §37).

33. Standing Waves.

When the length of that part of the line on which reflection is taking place coincides with the half-length of the electric wave, the phenomena are more important and, if the source of disturbance is maintained, a permanent state of abnormally high voltage may be established. The wave length depends only upon the electrical constants of the circuit. If the capacity K and inductance L are concentrated, the frequency of free electrical movement, that is, the number of complete swings per second, is—

$$f = \frac{1}{2\pi} \frac{1}{\sqrt{K \,.\, L}}.$$

The corresponding wave length $\lambda = v/f = 2\pi v\sqrt{KL}$; where $v = 3 \times 10^{10}$ cm. per sec. For example, when the inductance is 1

microhenry and the capacity 10 millimicrofarads—

$$\lambda = 6{\cdot}28 \times 3 \times 10^{10}\sqrt{(10^{-14})} \text{ cm.}$$
$$= 188{\cdot}4 \text{ metres.}$$

Thus, if AB (Fig. 29) is the developed length of a line, A being a terminal of a generator

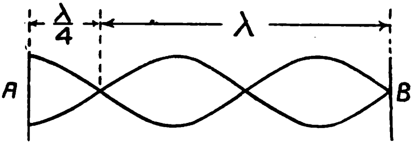

FIG. 29.—STANDING VOLTAGE WAVES ON A TRANSMISSION LINE.

of surges such as a spark gap and B an open end of the line, then since there is maximum voltage at A, there will be apparent standing waves when the distance AB is $\frac{\lambda}{4}$ + a multiple of $\frac{\lambda}{2}$. A line with both ends open will resonate if struck by lightning when its length is a multiple of $\lambda/2$. When the maximum voltage of these waves exceeds 100,000 the change from points of high to those of low voltage can be seen in the dark by the corona or brush discharge

on the wire. There appear to be standing waves of brightness. The phenomena of standing waves can readily be illustrated by the oscillograph.

34. Resonance.

Everyone is familiar with the fact that to work up the swing of a heavy pendulum it is necessary to time the impulses to coincide with the free period. Soldiers must break step when crossing a suspension bridge for fear that the period of their tread may coincide with that of the bridge. A single-cylinder motor-bicycle may at certain speeds vibrate vertically in an alarming manner. It is by the phenomena of sound that this effect can be most strikingly illustrated, and it is there known as resonance. Wherever there is coincidence between the time of vibration of a system having a free period and that of the disturbing force there is said to be resonance.

Transient standing waves may be set up by reflection along a wire stimulated by shock, but when the frequency of an alternator connected to a line coincides with the frequency as calculated above, the resonance that occurs will set up voltages much higher than that of

the alternator, unless there is resistance in the line to limit the current, in the same way as friction damps the swings of a pendulum.

Consider the case of Fig. 30, with capacity K, inductance L, and resistance r in series with an alternating current generator of frequency f and voltage V.

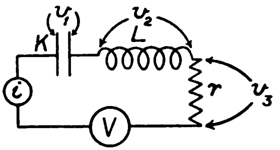

FIG. 30.—CIRCUIT CONTAINING CAPACITY, INDUCTANCE, AND RESISTANCE.

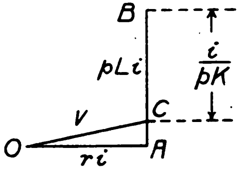

FIG. 31.—VOLTAGE VECTORS RELATING TO FIG. 30.

The voltages v_1, v_2, v_3 across the three parts of the circuit are, taken added in their proper phase relations, equal to V. $v_1 = i/pK$, $v_2 = pLi$, $v_3 = ri$, where i is the circuit current. These are shown in their correct phase relations in Fig. 31. When $pLi = \frac{i}{pk}$, the two voltages v_1 and v_2 are equal and opposite, AB drawn upwards BC downwards. The whole voltage of the alternator is then applied to the

resistance r, since the others cancel, and the current $i = V/r$, which may be very large, so that v_1 and v_2 are great.

Example.—Let $r = 2$ ohms, $L = 1$ henry, $K = 15{\cdot}8$ microfarads, $V = 1{,}000$ volts, $f = 40$. The capacity is chosen to give resonance, and the current $i = 500$ amperes.

Here

$$v_1 = \frac{i}{pk} = \frac{500 \times 10^6}{2\pi \times 40 \times 15{\cdot}8} = 125{,}600 \text{ volts.}$$

$$v_2 = pLi = 2\pi \times 40 \times 1 \times 500$$
$$= 125{,}600 \text{ volts.}$$

$$v_3 = ri = 1{,}000 \text{ volts.}$$

In circuits with zero resistance, like those of Professor Kammerlingh Onnes of Leyden at the boiling point of helium, the least applied pressure would give rise to infinite voltages under such conditions.

The frequency of resonance in this case of *concentrated capacity and inductance* is $f = \dfrac{1}{2\pi\sqrt{KL}}$. If the capacity and inductance are *distributed*, the natural frequency is no longer single but is given by $f = \dfrac{2k+1}{\sqrt{KL}}$; in

which $k = 0, 1, 2, 3 \ldots$, so that the line may resonate at an indefinite number of frequencies, and the voltage distribution be as that of Fig. 29, that is, having maxima and minima along the line.

35. Influence of Load on Resonance.

Resonance consists in a transfer of energy from electrostatic to electromagnetic, and if there were no absorption or radiation of energy this oscillation would go on indefinitely. While not actually preventing resonance, load damps it out rapidly by withdrawing energy from the electrostatic field into the wires, or during the establishment of the field, by radiating energy into space. The damping coefficient u, the reciprocal of the time taken for the amplitude of the current to fall to $1/\varepsilon$, i.e. $1/2{\cdot}718$ of its initial value, can be shown to be $\frac{1}{2}\frac{r}{L}$.

Thus, in the case of a transmission line on light load, if $r = 0{\cdot}1$ ohm and $L = 0{\cdot}01$ henry, then $u = \frac{1}{2}\,\frac{0{\cdot}10}{0{\cdot}01} = 5$. It therefore takes $\frac{1}{5}$ sec. for the surge power voltage or current to fall

to $1/\varepsilon$, or approximately one-third of its first value.

When, however, the line is loaded and transmitting 1,000 kilowatts, with 100 amperes flowing, the equivalent resistance $r = W/i^2 = 100$ ohms. Assuming for the argument that the inductance does not change, $u = \frac{1}{2}\frac{100}{0{\cdot}01} = 5{,}000$, and the oscillations are almost instantly reduced to a negligible value. Free resonance cannot be maintained, and forced resonance is damped out too heavily to give rise to high voltage by reflection.

36. Resonance in Three-phase Systems.

Consider first a delta-connected system. The only capacity which can be present,

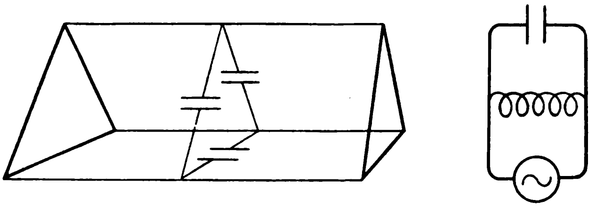

FIG. 32.—EQUIVALENT CIRCUIT OF THREE-PHASE DELTA-CONNECTED SYSTEM.

other than that of the windings, is that between phases (Fig. 32). The arrangement is then

identical with an inductance, that of the load, and a capacity in parallel across the generator terminals. In such a case there can be no general resonance as the voltage on the terminals of the capacity or inductance cannot be higher than that of the generator, for the system would then discharge through it. It is, however, possible to have waves of small energy along the line between the machines.

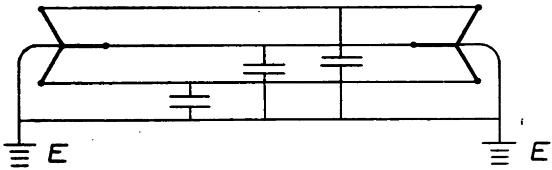

FIG. 33.—THREE-PHASE STAR-CONNECTED SYSTEM WITH EARTHED NEUTRAL.

In a star-connected system (Fig. 33) there is as before the capacity between phases, not shown in the figure. If, however, the two neutral points be earthed, forming a four-wire circuit, the capacity between any phase and the neutral is in series with the inductance of that phase. The system is then liable to resonate to earth on the third harmonic or any multiple of it.

37. Surge Impedance.

The problems of waves along wires have been discussed very fully by mathematical physicists. Steinmetz was, however, the first

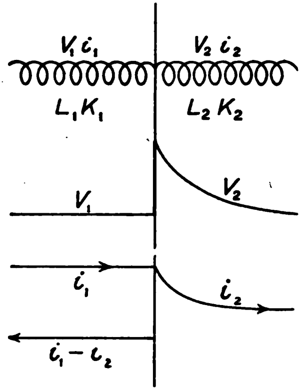

FIG. 34.—MEAN VOLTAGE AND CURRENT CONDITIONS IN THE LEADING-IN COILS OF A TRANSFORMER.

engineer to deal with surges and transient phenomena and the practical problem of voltage rise in a simple and powerful manner. His treatment will be followed here.

The maximum kinetic energy of a surge is $\frac{1}{2}Li_0^2$, where i_0 is the maximum of the surging current. The maximum potential energy is $\frac{1}{2}KV_0^2$, where V_0 is the crest value of the

surge voltage. But where the resistance is negligible—

$$\tfrac{1}{2} L i_0^2 = \tfrac{1}{2} K V_0^2, \text{ so that } \frac{V_0}{i_0} = \sqrt{\frac{L}{K}}.$$

This ratio of maximum voltage to maximum current Steinmetz calls the *surge impedance.*

In the case of a transformer (Fig. 34) having an impedance L_2 and capacity K_2 at the moment of connection to a line of which the constants are L_1, K_1, then, since at the point of connection there is no dissipation of energy we may write, $V_1 i_1 = V_2 i_2$. But $\dfrac{V_1}{i_1} = \sqrt{\dfrac{L_1}{K_1}}$ and $\dfrac{V_2}{i_2} = \sqrt{\dfrac{L_2}{K_2}}$,

therefore the ratio of the two voltages

$$\frac{V_2}{V_1} = \sqrt[4]{\frac{L_2 K_1}{L_1 K_2}}, \text{ and } \frac{i_2}{i_1} = \sqrt[4]{\frac{L_1 K_2}{L_2 K_1}}.$$

Writing $\sqrt{\dfrac{K}{L}} = z$, we have—

$$\frac{V_2}{V_1} = \sqrt{\frac{Z_2}{Z_1}} \text{ and } \frac{i_2}{i_1} = \sqrt{\frac{Z_1}{Z_2}}.$$

This means that the ratio of the surge voltage in the leading-in coils to the voltage in the

line is proportional to the square root of the ratio of the surge impedances.

Since all the current does not enter the winding, on account of the choking effect of the latter, the difference i_1-i_2 is reflected and forms a wave back along the line.

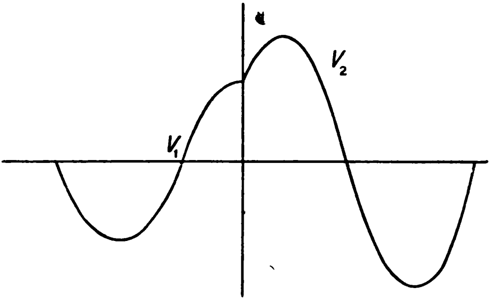

FIG. 35.—ILLUSTRATING RISE OF SURGE VOLTAGE AFTER ENTERING WINDING.

To consider *instantaneous voltages*, rather than mean or maximum voltages, let V_1 be the voltage wave at the moment of reaching the transformer. At the point of contact there is a common ordinate but immediately after the surge voltage in the windings rises (Fig. 35). It is not only at the extreme end of the winding that trouble is to be feared, but V_2 may rise as the wave penetrates and reach a maximum

within. It is, therefore, necessary to insulate heavily not one but several of the leading-in turns.

38. Change from Overhead to Underground Lines.

Electrical supply in a colliery district is characterized by frequent change from overhead to underground transmission. The ratio of surge voltages in such a case is—

$$\frac{V_2}{V_1} = \sqrt[4]{\frac{L_2 K_1}{L_1 K_2}}.$$

But in changing from overhead to underground lines, K_2 is greater than K_1, and L_2 is less than L_1, so that the product of inductance and capacity may well be the same. In such a case there is no shock, no reflected wave, and no rise in voltage. If suitably designed, the sub-station is protected by the use of a leading-in length of underground cable, since this acts as an elastic buffer, the greater capacity taking up more transient charge per unit length of cable when struck by lightning, for example, for a given safe rise of voltage limited by the arrester.

39. Lightning Discharges.

The chief point to be realized when dealing with lightning is the extremely small *quantity* involved. The voltage set up by the introduction of a quantity q into a system of capacity K is q/K. Take $K = 0{\cdot}01$ microfarad, not a large value for a transmission line, and let $q = 1$ ampere-second, a small value in electrical engineering. We have then $V = 1/(0{\cdot}01 \times 10^{-6}) = 10^8$ volts. Pressures of this enormous value are not common, even in systems in South Africa. Many estimates of the current in a lightning flash have been made up to a million amperes. It is probable that the total quantity does not reach one ampere-second. The flash is known from photographic records to last a time of the order of one-millionth to a ten-thousandth of a second. To discharge two areas 100 metres square separated by 1,000 metres of air charged to 1,000 million volts, in one-millionth of a second gives a current of 100,000 amperes. The work done is 33 million foot-pounds, and the horse-power is sixty thousand million, yet the quantity discharged is only 0·10 ampere-second.

40. Influence of Sudden Bends.

When the current is steady or alternating at low frequency, sudden bends on a conductor have no effect, but with lightning discharge, or oscillations of "wireless" frequency the charge may pile up at a corner and jump across rather than go round. Wherever a lightning conductor is bent to follow mouldings, at the foot of a high chimney, for example, the stonework is invariably blackened by discharge, and it is interesting to watch such a place during a thunder storm. There is a continual flicker as the disturbances are picked up by the conductor acting as an aerial, and go to earth at the bends.

41. Normal Transients. Direct Current Circuits with Resistance and Inductance.

There are many transient phenomena which occur in the normal working of transmission circuits, and which are not surges from one form of energy to another. Consider the simplest case of a direct current circuit arranged as in Fig. 36.

With the switch in position a the steady current $i = e/r$, and in position b it becomes

for the moment $i = e^1/(r + r^1)$. When the inductance is large the switch can be thrown over from a to b without i changing; the current then falls to zero. At the moment of contact with b, $i = e^1/(r + r^1)$, where e^1 is the inductive voltage produced in the circuit

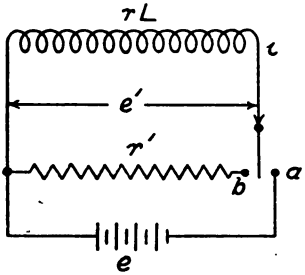

FIG. 36.—DIRECT-CURRENT CIRCUIT WITH RESISTANCE AND INDUCTANCE.

by the current trying to change. We have then—

$$\frac{e^1}{e} = \frac{r + r^1}{r}.$$

Take, for example, $r = 5$ ohms, $r^1 = 100$ ohms, and $e = 10$ volts, then $e^1 = 10 \times 105/5 = 210$ volts. This voltage is derived from the collapse of the magnetic field in the inductance L. If r^1 is high, or when the circuit

is broken rapidly without an arc, the voltage can rise to extremely high values.

Consider next the current when contact is made at a. In all problems in which it is required to find the current in a circuit we start by writing down the voltage equation and solving it to obtain current.*

The voltages are that of the cell, the back electromotive force from the inductance, and the drop in the resistance. Here—

$$\frac{dN}{dt} + ri = e$$

and, since $N = Li$ and L is taken as constant—

$$L\frac{di}{dt} + ri = e.$$

This is converted into a current equation by dividing each side by r, thus—

$$\frac{L}{r}\frac{di}{dt} + i = \frac{e}{r}.$$

* The following equations are in all the text-books, but are written down to illustrate the reasoning behind the simplest cases. When the voltage is alternating the analysis is more intricate, but at the start and stoppage of an alternating current the envelopes of the curves have the same transient forms as in Fig. 37.

But $e/r = i_0$, the final steady current, hence—

$$\frac{L}{r}\frac{di}{dt} = i_0 - i.$$

Transposing and integrating, we have—

$$\int \frac{di}{i_0 - i} = \int \frac{r}{L} dt$$

or
$$-log\ (i_0 - i) = \frac{rt}{L} + C,$$

where C is the constant of integration.

To find C, $i = o$ when $t = o$, and $C = -log\ i_0$. Hence—

$$log \frac{i_0 - i}{i_0} = -\frac{rt}{L},$$

or
$$i = i_0 (1 - \varepsilon^{-rt/L}).$$

The current, therefore, varies with time, and when t is large the current is steady; the variation is transient.

In the very important practical case in which r^1 (Fig. 36) is zero, so that throwing the switch on to b short-circuits the inductance we have for the voltage equation—

$$L\frac{di}{dt} + ri = o.$$

The cell is cut out and the current continues to flow until the energy $\frac{1}{2}Li_0{}^2$ of the magnetic field is all dissipated as ri^2 in the windings.

Writing the above $\int \frac{di}{i} = -\int \frac{r}{L} dt$

$$log\ i = -\frac{rt}{L} + C.$$

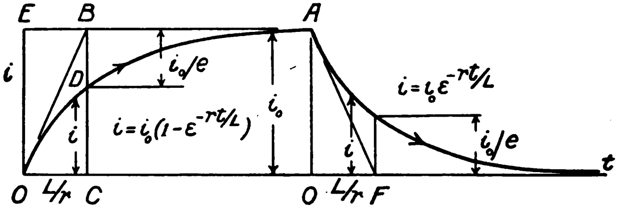

FIG. 37.—CURVES OF CURRENT INCREASE AND DECREASE IN CIRCUIT CONTAINING RESISTANCE AND INDUCTANCE.

When $t = o$, $i = i_0$ the current before short circuit, and $C = log\ i_0$; and finally—

$$i = i_0\ \varepsilon^{-rt/L.}$$

These curves are given in Fig. 37.

Since $\frac{rt}{L}$ must clearly be a number $\frac{L}{r}$ is a time. It is the time taken for the current to rise within (i/ε)th of its full value or to fall

to (i/ε)th of its initial value, and is known as the *time-constant* of the circuit. For field magnet windings it may be as much as a minute, for the coils of a direct current generator about 1/2,000th of a second. It is found from a curve of rise or fall recorded by an oscillograph by drawing a tangent at the start and dropping a perpendicular from the point at which this cuts the opposite bounding line, B (Fig. 37) when rising, F when falling. The lengths OC or OF in seconds, on the time base, are the time constant of the circuit, for in the short-circuit case $\dfrac{L}{r}\dfrac{di}{dt} = i_0$ at the start, and in Fig. 37 $\dfrac{di}{dt} = \tan AFO = \dfrac{AO}{OF}$, $Ao = i_0$, so that $OF = L/r$.

For alternating current transmission systems L/r must always be small, and preferably less than the periodic time of the system, though in many cases it is nearly equal to the periodic time.

Multiplying the ordinates BC-DC by the circuit resistance they represent instantaneous back electromotive force, for this is $dN/dt = e - ri$. In the figure e now $= OE$, and any

ordinate $= ri$. A line drawn from EA to the curve represents $e - ri$, and since $dN = (e - ri)dt$ the area OEA denotes all the magnetism that is linked with the inductive winding. This all comes out on short-circuit.

In the case of an actual field coil of which the inductance is 55 henries and the magnetizing current 10 amperes, the energy stored $\frac{1}{2}Li^2 = \frac{1}{2}\cdot 5500 = 2{,}750$ joules or 2,000 foot-pounds, and this is not lightly stopped. If the circuit is broken in $\frac{1}{10}$ second, the mean voltage on the terminals $= L.di/dt$ is $55 \times 10/0\cdot 1 = 5{,}500$ volts. This energy and voltage would be fatal to any one taking the shock from hand to hand by breaking the circuit.

42. Direct Current Electrostatic Transients.

Replacing the inductive resistance of Fig. 36 by a capacity we have Fig. 38. Closing the switch on a, the condenser is instantly charged to the voltage V. Throwing it over to b, the condenser discharges through r. The voltage equation is then—

$$v = Kr\frac{dv}{dt}.$$

For $q = KV$, $i = \frac{dq}{dt} = K\frac{dv}{dt}$, and $v = ri$.

Thus $\int \frac{dv}{v} = \int \frac{dt}{Kr}$ and $v = V\varepsilon^{-t/Kr}$.

Here $1/Kr$ is the coefficient of decay of the circuit and, by observation of the rate of decay

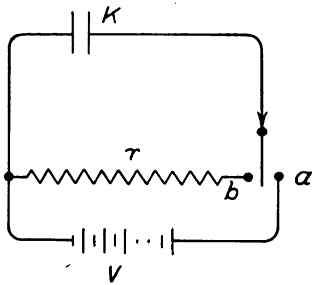

FIG. 38.—DIRECT-CURRENT CIRCUIT WITH RESISTANCE AND CAPACITY.

of the voltage, K or r can be found if the other is known.

The interest of the case in transmission is that if the leakage resistance r is large—many megohms—and K also large, the decay of voltage of an insulated line may be extremely slow, and fatal shocks have been had from a neglect of this. It is necessary to dead short-circuit a line which has been standing after

load before touching the conductor, the resistance of the insulation may be so high that the residual charge cannot escape.

A cable system of 10 microfarads capacity charged to 10,000 volts has $\frac{1}{2}KV^2 = \frac{1}{2}\frac{10}{10^6} \cdot 10^8$, 500 joules or 370 foot-pounds available for instant discharge. 250 foot-pounds would be discharged through a resistance of 2,000 ohms from hand to hand in $\frac{1}{50}$th second at a rate of 30 horse-power, sufficient to be fatal.

43. Steinmetz's Treatment of Alternating Current Transients.

The following are typical illustrations of the alternating transients usually encountered. When a circuit is switched-in the *current* must always start from zero, even though the current wave may not be passing through its zero value at the moment of switching-in. Curve (1) (Fig. 39) shows the rise of the current when switching-in from no-load away from the zero point of the current wave. The zero line immediately jumps up to the instantaneous value of the wave, after which the curve gradually settles down to the true zero line,

as shown, along the transient as the centre line. The value of the transient i_1 at any instant during the transition period $= i_0 \, \varepsilon^{-rt/2L}$. If by any chance the moment of switching-in

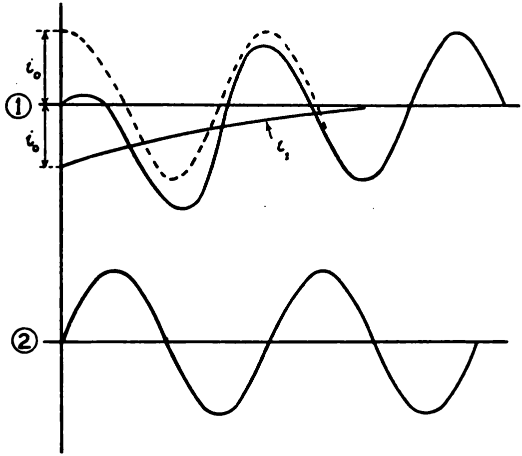

FIG. 39.—SWITCHING-IN LINE FROM NO-LOAD.

(1) Away from zero point of current wave.
(2) At zero point of current wave.

coincided with the zero value of current there would be no transient, and the curve would be perfectly symmetrical from the start, as in (2) Fig. 39.

The dotted curves in Figs. 39, 40, and 42 represent the alternating current when it has

reached a steady state, but produced backwards to zero in order to show the change which takes place then. Thus in (2), Fig. 39, there is no transient change. In (1), the current having to start from zero, whatever the voltage may be at switching-in, has the

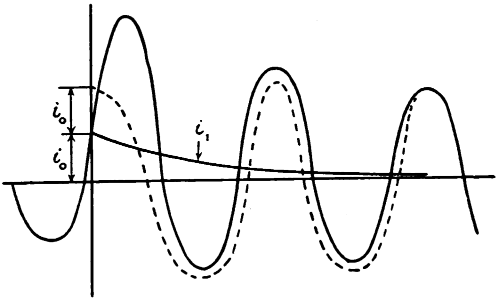

FIG. 40.—CHANGE OF CURRENT WAVE ON CHANGE OF LOAD.

same shape as the dotted curve, but is displaced, so that the full line is a copy of the dotted line only starting from zero.

Now consider the case of a change of load: This will usually cause a corresponding change in the angle of lag and the maximum value of the current will also not necessarily be the same. The current cannot jump, however, and therefore continues from the same value,

but the centre line jumps above the zero line, as in Fig. 40, by an amount equal to the difference between the instantaneous current before the change and that which it would have had after the change if it could have

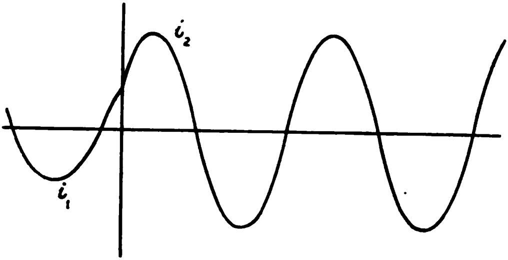

FIG. 41.—CURRENT CURVE AT SWITCHING-IN WITHOUT CHANGE IN ANGLE OF LAG.

taken that value instantly; and, as before, will settle down after a few oscillations. Again the value of the mean current i_1 at any instant during the transition is given by $i_1 = i_0 \varepsilon^{-rt/2L}$.

Consider the two extreme cases. Supposing that on switching-in there is no change in the angle of lag, the curve will then continue the same, as in Fig. 41, and there will be no transient, merely a change of amplitude. The curve is, as it were, refracted, but is

symmetrical about the zero line after as well as before the change. This, however, is the best possible case; the extreme worst case would be as in Fig. 42, where the change in

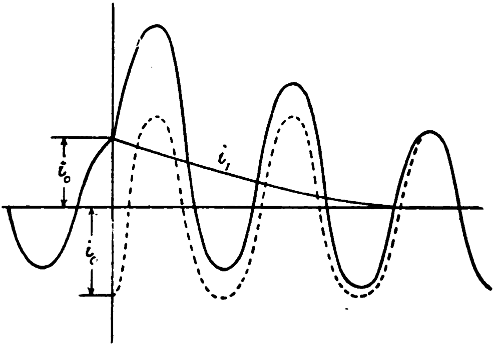

FIG. 42.—SWITCHING-IN WITH 90 DEGREES CHANGE IN PHASE.

phase amounted to 90 degrees. The zero point would jump to the instantaneous value i_0 and the current would oscillate about the line i_1, gradually settling down to the true zero line. The maximum amplitude from zero would, however, be much larger than in the previous cases, owing to the greater phase difference, and the current is at first unsymmetrical about the horizontal zero line.

44. Three-phase Machines.

Suppose that a three-phase machine, of which the armature current is shown in Fig. 43A, is thrown suddenly on to heavy load.

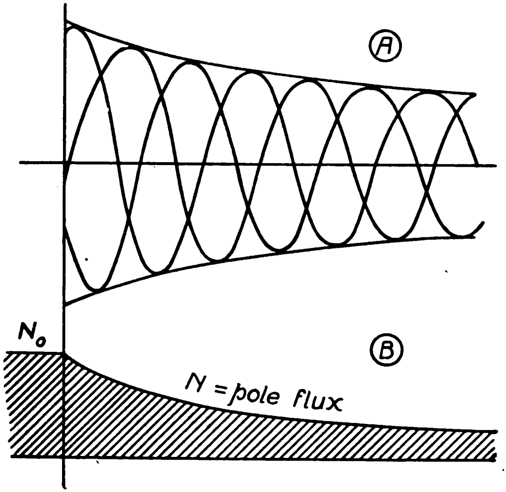

FIG. 43.—ARMATURE CURRENT AND POLE FLUX IN THREE-PHASE MACHINE THROWN SUDDENLY ON TO HEAVY LOAD.

If the machine speed and the field are maintained the same there is no reason why the current should decay slowly. When, however, the load is thrown on there is a back magnetizing field expressed by $X_b = \frac{3\,IT}{\sqrt{2}}\ sin\ \phi$,

where I = the current and T the number of armature turns per phase. In the worst possible case, which is that of short circuit, $sin\ \phi = 1$. As the field is weakened by the back magnetization the flux decays to a steady

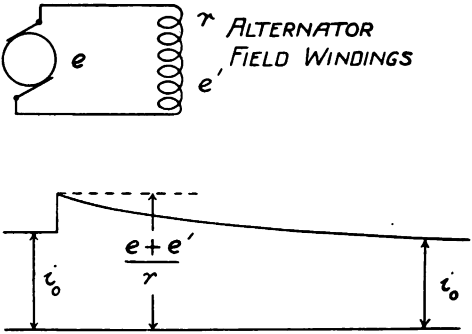

FIG. 44.—FIELD CURRENT AT AND AFTER SHORT-CIRCUIT ON MACHINE.

value as shown in Fig. 43B, and the currents fall as in Fig. 43A.

In the case of a short circuit on a machine, what really happens to the magnetization is that, at the moment the back magnetizing turns come into action, the field begins to be wiped out, but in dying out it induces in the field winding a voltage e^1 which tends to maintain the field. The new field current will be $(e + e^1)/r$ at the moment of short circuit.

At this moment then the field current rises and then gradually falls again to the steady value i_0, as shown in Fig. 44. In a three-phase machine the field current is supposed to be free from pulsation; actually there is often a slight ripple on it.

45. Single-phase Machines.

In the case of single-phase machines the armature and field currents on symmetrical short circuit are shown in Figs. 45 (*a*) and (*b*) respectively. If the current is symmetrical at the start, there will be a double frequency pulsation in the field current superposed on the smooth change of Fig. 44. When the current is asymmetrical, as in Figs. 40 or 42, or 45C, the field current pulsation is not symmetrical, but is as shown in Fig. 45D. The reason for these pulsations of field current is that the armature reaction of a single-phase machine is not steady, but pulsating, and induces a corresponding pulsation in the field circuit by direct transformer action. In all cases of transient phenomena of magnetic machinery it will be found that one or other of the forms described above will apply. Full information regarding the above curves

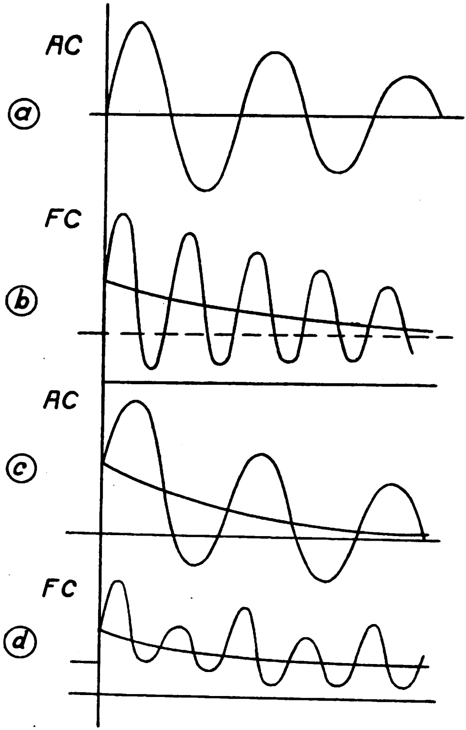

FIG. 45.—SHORT-CIRCUIT CONDITIONS IN SINGLE-PHASE MACHINE.

(*a*), (*b*) Armature current (AC) and field current (FC) on symmetrical short-circuit.

(*c*), (*d*) Asymmetrical armature current (AC) and field current (FC).

may be found in Steinmetz's books on transient phenomena. The only other typical transients are in the *magnetization of transformers*.

In the case of switching-in a transformer, such as an instrument transformer, the initial current depends upon the position on the curve of magnetization. If the switch is

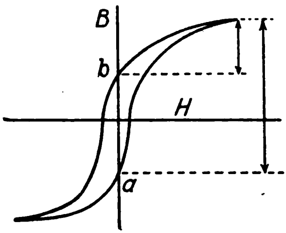

FIG. 46.—MAGNETIZATION CURVE FOR INSTRUMENT TRANSFORMER.

closed with the magnetization in the position *a* (Fig. 46) then the back electromotive force at the moment will be large, and the switching-in current will therefore start with a low value, rising to the normal. If, however, the switch is closed with the iron in the condition *b* on the magnetization curve there will be little flux to oppose the first rush of current, and the first few oscillations may have values as much as 70 times the normal value when

iron of too high retentivity is used for the transformer cores.

46. Direct Current Arcs at Break.

The fall of current in an inductive circuit opened by a switch is a function of the resistance of the arc. We have shown (§ 41) that on short-circuiting a coil of resistance r and inductance L through a resistance r^1, $i = i_0\, \varepsilon^{-(r + r^1)t/L}$. The more complete case is given by the equation—

$$L\frac{di}{dt} + i\, f(r^1,t) + ri = o,$$

where the resistance of the arc varies with time and is represented by $f(r^1, t)$.

By giving various forms to the function, such as taking $r^1 = kt$ or kt^2, solutions can be found. The current falls at first quickly, then remains nearly steady for the greater part of the break, then drops suddenly to zero.

47. Alternating Current Arcs at Break.

An arc at the point of interruption of an inductive circuit carrying an alternating current differs from a direct current break chiefly in the fact that the current changes very slowly by comparison. The current wave

can, in fact, be identified readily in oscillograph records by its unchanged form after break. At the point from which an arc begins when the poles are separated there is always

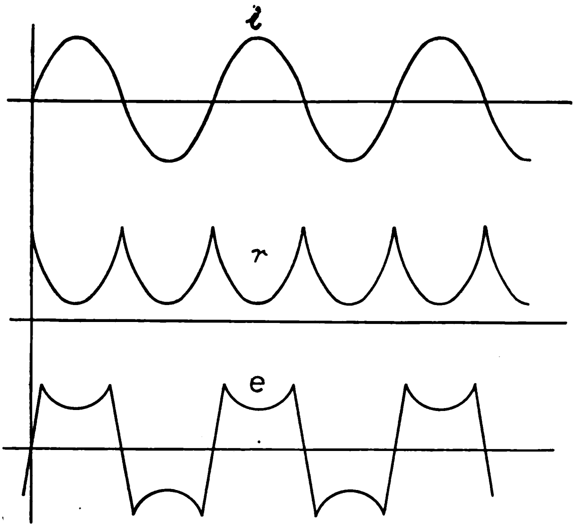

FIG. 47.—CURRENT (i), ARC RESISTANCE (r), AND VOLTAGE (e) CURVES FOR AIR-BREAK SWITCH WELL OPEN.

a high resistance. As the current increases the resistance decreases. The voltage across the break has a curious spiky form, especially in air breaks. This is a consequence of the variation of resistance of the arc with current

as in Fig. 47, where *i* and *e* are small portions of an oscillograph record of an air-break switch opening. The first part of the record of the voltage across a high tension air break switch is shown in Fig. 48.

The current breaks by the mechanical instability of the arc caused by convection

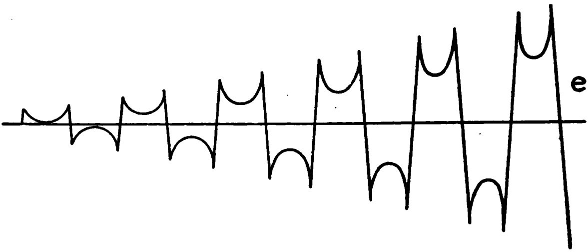

FIG. 48.—RECORD OF VOLTAGE ACROSS HIGH TENSION AIR-BREAK SWITCH WHEN OPENING.

currents deflecting the stream of electrons from the line of the poles, and by the cooling of the latter so that thermionic emission ceases at the same time as the intensity of the electric field is diminishing. Ionization by collision fails and the conducting path is broken.

48. Oil-break Switches.

In the operation of an oil-break switch there are both electrical and mechanical transient

effects. At the moment of making the circuit there is no appreciable arc, and any gases which may be liberated can safely be neglected. At break, however, there are several factors to be considered, viz., the load, or kilovolt-amperes, to be broken, the velocity and acceleration of the moving parts, the influence of magnetic fields, the reaction of the mass of oil, the nature of the oil, the air space above it, and the gases formed by the arc.

At the moment of separation the space between the poles is occupied by metallic vapour and, since the shape of the arc follows that of the electrostatic lines of force, it is at first a flattened cylinder and later approximately spherical. The oil in contact with and to some small extent penetrating the arc is vaporized. This vapour is rapidly dissociated to hydrogen and methane as the chief gases. There is also the vapour of copper from the poles.

From experimental records the maximum voltage that large arcs have before break is nearly 1,000. It rises uniformly and the mean value may then be taken as about 500 volts. When the time of break is 0·05 second, the heat generated by the break of 10,000 amperes

will be approximately 250 B.Th.U. Now the melting point of copper is 1,084° C., and its boiling point is 2,310° C., whilst the temperature of the arc is that of its vaporization. There is, therefore, an ample margin of temperature to melt the copper, some 40 grammes of which might be melted off if the whole of the energy of the arc were spent in doing so.

Next consider the action of the arc on the oil. It takes, say, 100 gramme-calories to crack or vaporize 1 gramme of oil, and, therefore, about 630 grammes of oil would be vaporized in the case considered, which is equivalent to a short-circuit on a system of moderate size. Taking, after trials, about 20 cubic centimetres of gas per gramme of oil the vaporization of 630 grammes means the liberation of 12,600 cubic centimetres, 12·6 litres in 0·05 second, a rate of nearly 9 cubic feet per second. Such a cavity must develop upwards, it cannot go downwards. The rate of rise of the top of the cavity is, therefore, twice that of the centre, that is, of the radius. The rate of increase of the radius—

$$\frac{dr}{dt} = \frac{1}{S}\frac{dV}{dt},$$

where S is the surface of the cavity and V its volume.

Thus at the start, when S is small, $\frac{dr}{dt}$ may be very large (*see* Fig. 49), and there is

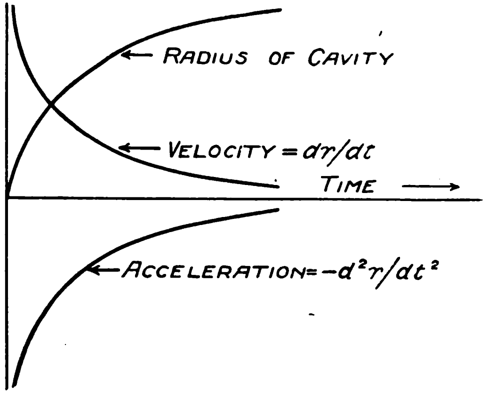

FIG. 49.—FORMATION AND MOVEMENT OF CAVITY IN OIL OF OIL-SWITCH DUE TO ARC.

a powerful pressure wave sent through the oil, followed by the sustained but falling pressure in the cavity.

What, then, is the mechanical effect of the formation of the cavity in so short a time? As the arc extends, the top of the cavity rises and, in doing so, forces back the oil. The force required to move a column of oil of

mass m over the arc with acceleration a is $F = m\,a$, where $a = 2\frac{d^2r}{dt^2}$.

Taking a cavity of 2 inches radius as the smallest from which a pressure wave of any destructive effect might spread, the corresponding rate of rise of the top of the cavity is 52 feet per second. In one-twentieth of a second it rises 2·6 feet, throwing the oil with great violence against the top of the chamber. But the pressure before it begins to rise, at the diameter of 4 inches, say, is $F = 2 \times \frac{52}{0{\cdot}005} \times m$ lb. per sq. in., the time 0·005 second being that to reach 4 inches diameter. Thus if the head of oil over the arc is 3 feet the weight is 1 lb. on a square inch and F = 650 lbs. per sq. in. It is in this stage that the high pressures are reached that start joints and form cracks, the damage being completed later by the expanding gas.

The question arises whether the damage done to a switch by a heavy short circuit is proportional to P, the maximum pressure, or to $\int Pe^{-at}\,.\,dt$, the time integral of the pressure. It is in all probability due to both.

The logical conclusion is to make the tank strong enough to resist the initial pressure without yielding to avoid any "follow-on" effects. When an oil switch tank yields to a heavy transient pressure its future behaviour is uncertain.

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